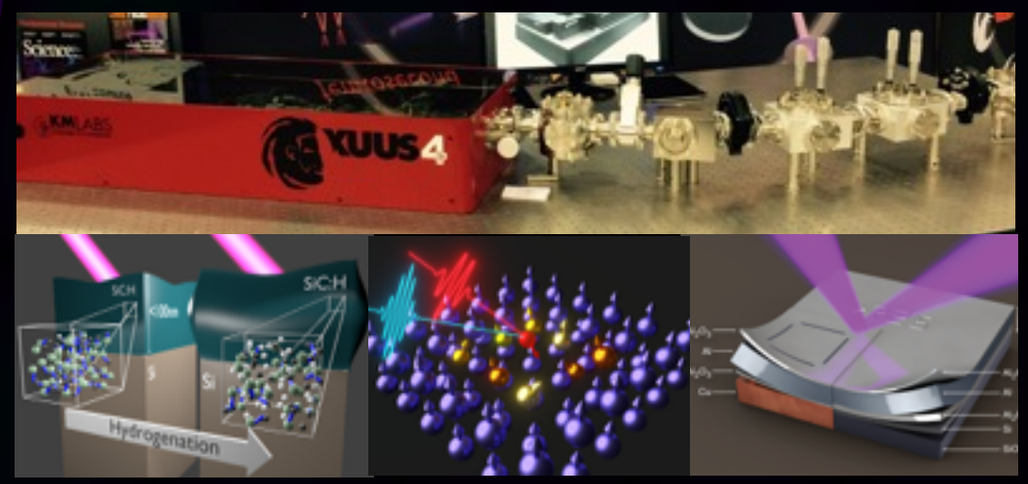
Full Field Imaging at 13.5nm in Reflection & Transmission Modes using Coherent High Harmonic Beams for Materials Inspection & Metrology

Christina Porter[1], Henry Kapteyn[1,2], Margaret Murnane[1,2] and Kevin Fahey[2]

[1]*JILA, University of Colorado at Boulder*

[2]*KMLabs Inc.*

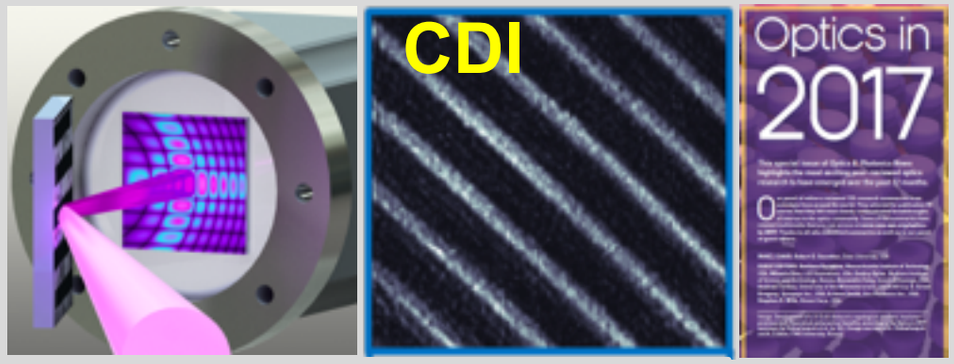


EUVL Workshop, June 13, 2018

Outline

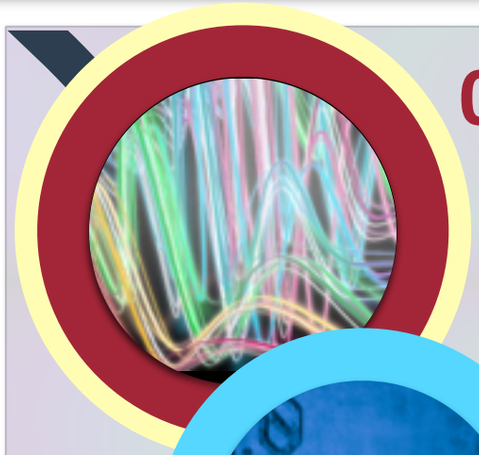
- **Advances in robust high harmonic sources**
  - Control over spectral, temporal & polarization state
  - Integrated engineered systems in VUV, EUV

- **Advances in tabletop imaging**
  - 1st sub-wavelength full-field EUV imaging
    - Record resolution: 12.6nm @ 13.5nm
  - Reflection and transmission mode CDI
  - Buried layer imaging
  - Complex imaging reflectometry: quantitative 3D chemical maps



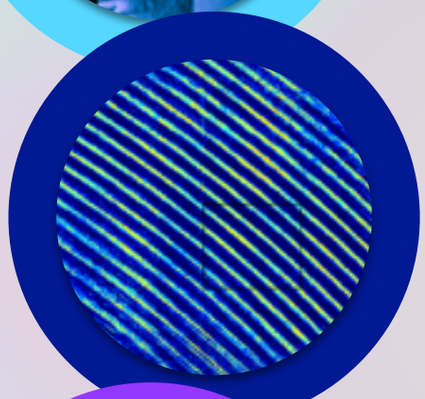
- **Perspective: potential for real EUVL Tools based on HHG**
  - Materials characterization: dopant profiling, interface characterization, thin film metrology, sub-surface imaging, photoelectron spectroscopy for in-situ materials etc
  - Mask inspection

PRESENTATION OUTLINE



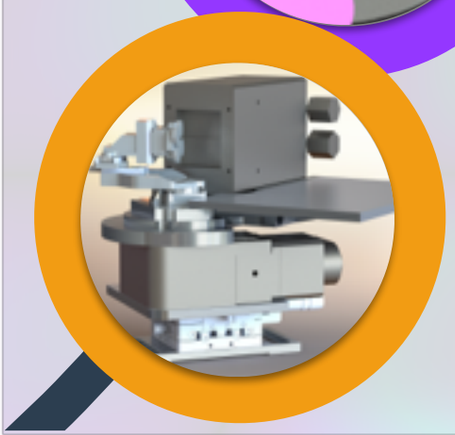
01 - INTRODUCTION

02 - 30NM BURIED LAYER IMAGING



03 - 13NM TRANSMISSION IMAGING

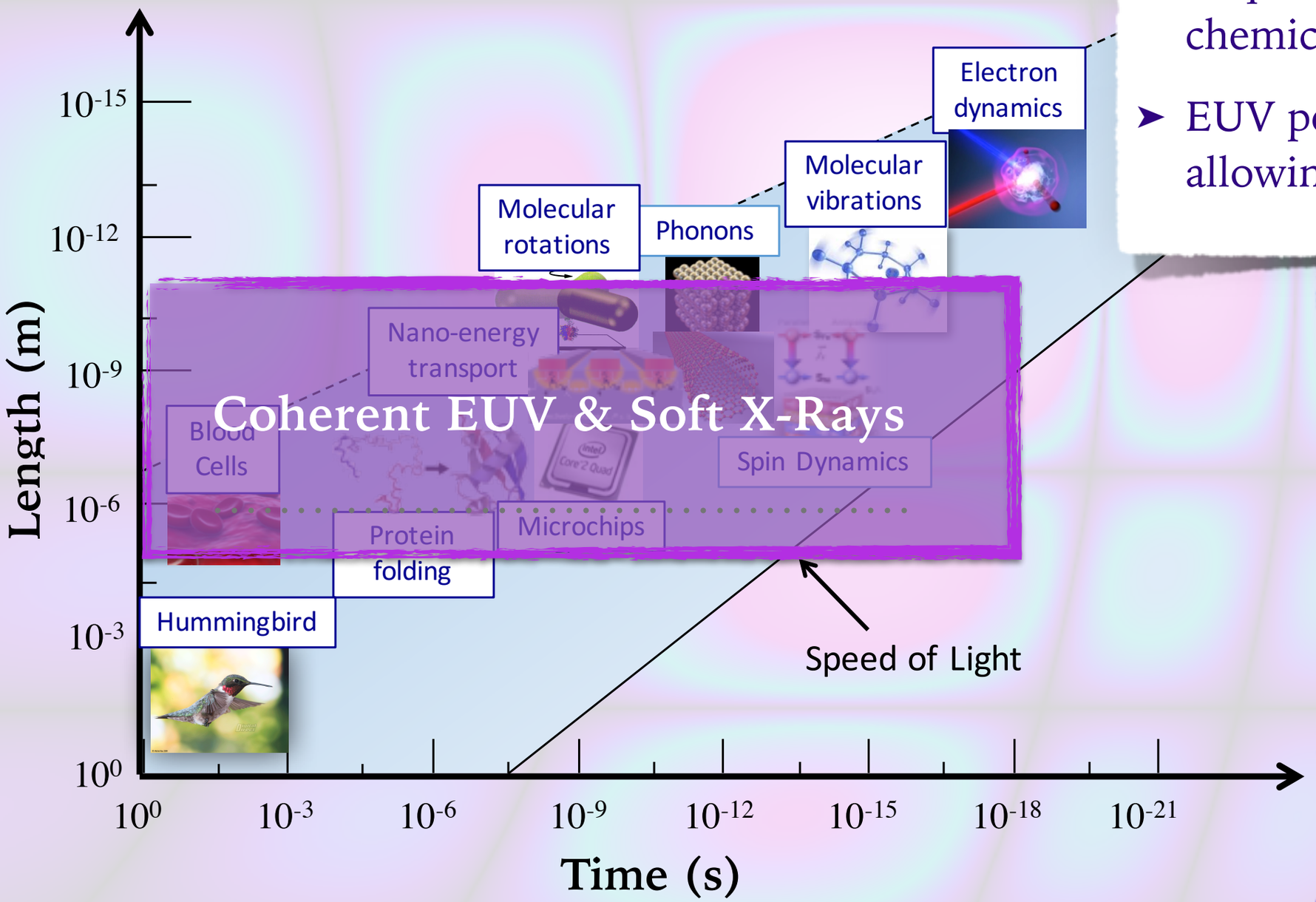
04 - 13NM REFLECTION IMAGING



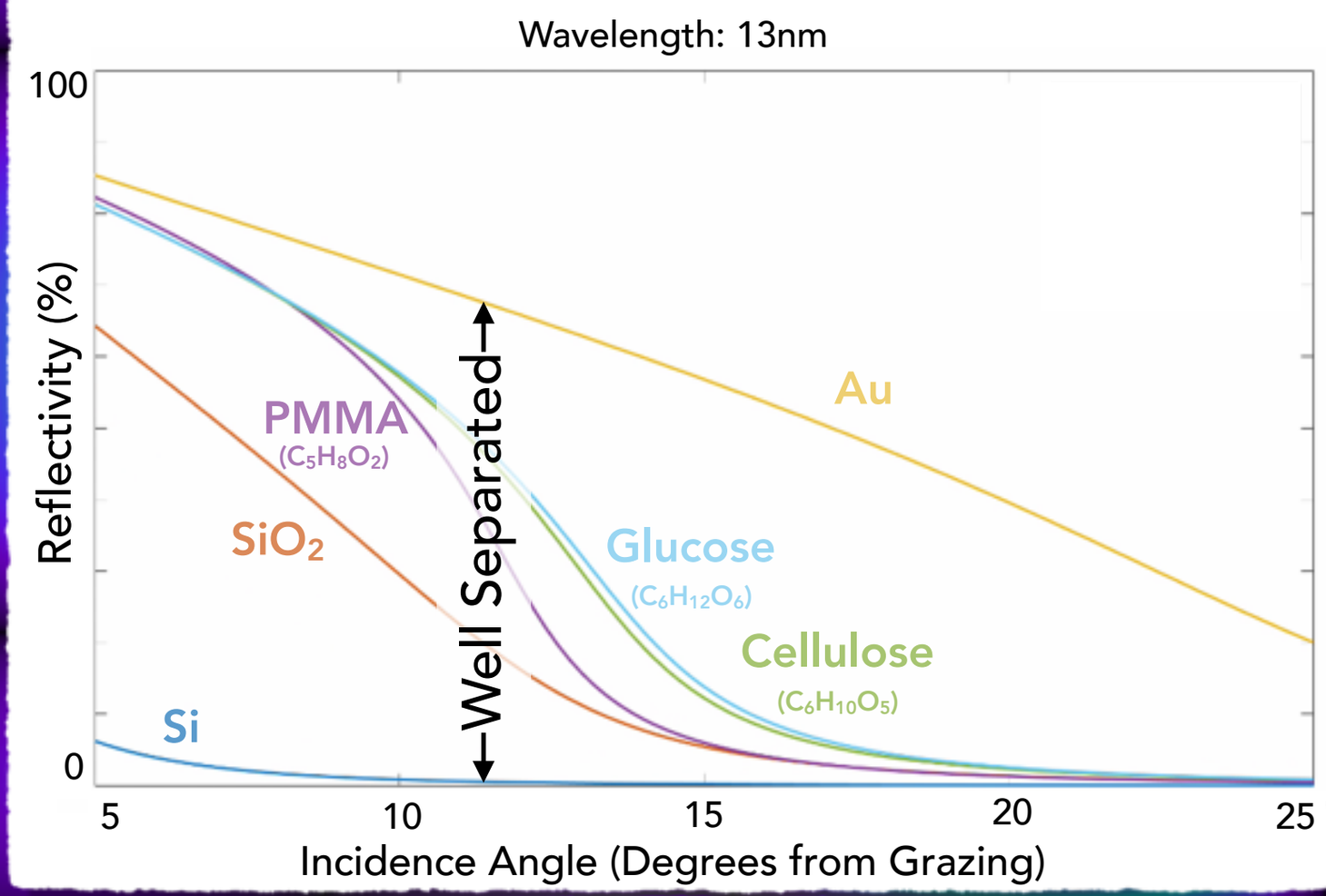
05 - 13NM COMPLEX IMAGING REFLECTOMETRY

EUV light is an ideal probe for the nano world

- Extreme Ultraviolet (EUV): $\lambda \sim 10–100$ nm
- Ultrahigh resolution imaging within the diffraction limit ($\sim\lambda/2$)
- Exquisite elemental contrast & chemical specificity
- EUV penetrates thick objects allowing buried layer imaging



EUV light is an ideal probe for the nano world



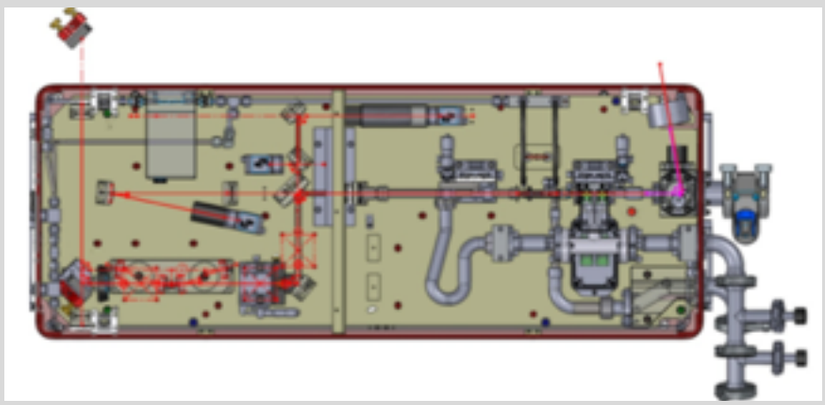
- Extreme Ultraviolet (EUV): $\lambda \sim 10–100$ nm
- Ultrahigh resolution imaging within the diffraction limit ($\sim\lambda/2$)
- Exquisite elemental contrast & chemical specificity
- EUV penetrates thick objects allowing buried layer imaging

13nm Light: important for actinic inspection

Also yields extreme chemical-sensitivity via angle-dependent reflectance.

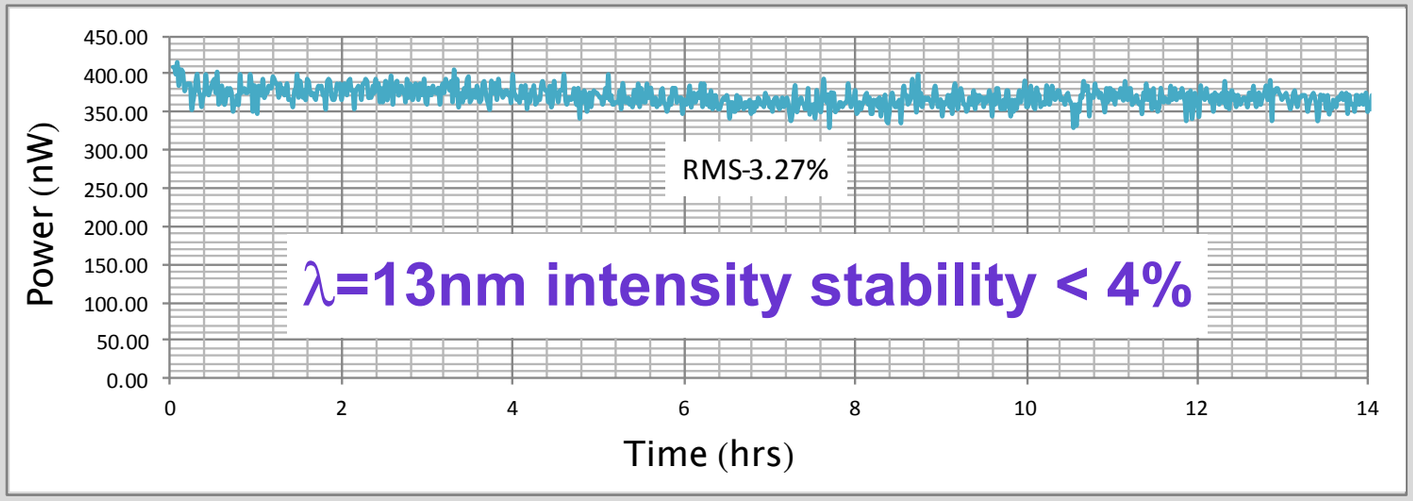
13nm light has many applications in materials science & industrial inspection/metrology tools

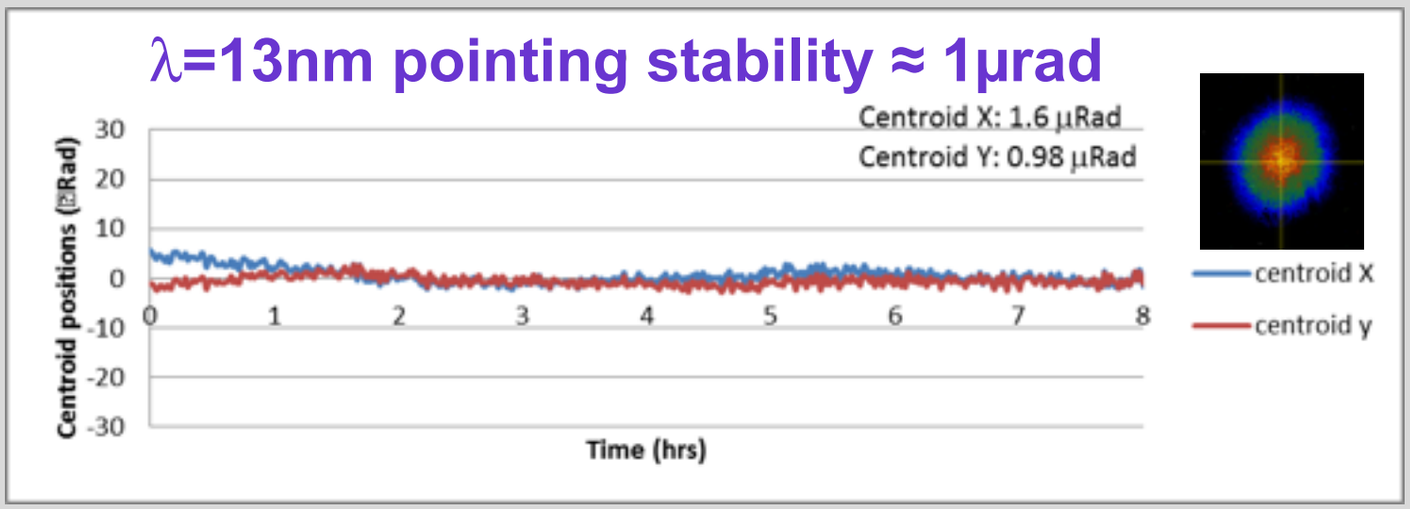
KMLabs XUUS: tabletop-scale ultrafast X-ray laser with visible-laser stability

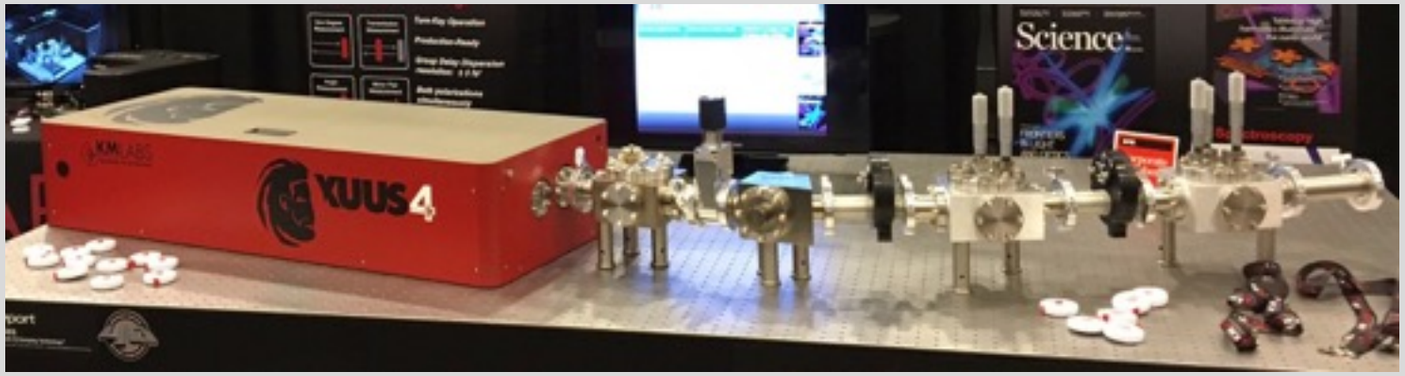


2009

2016



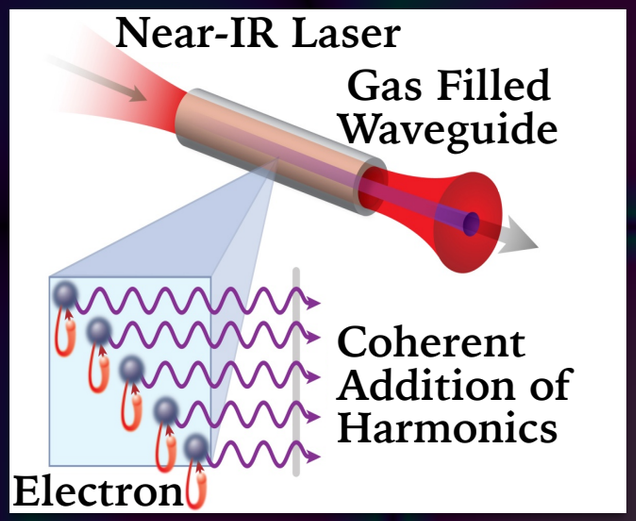


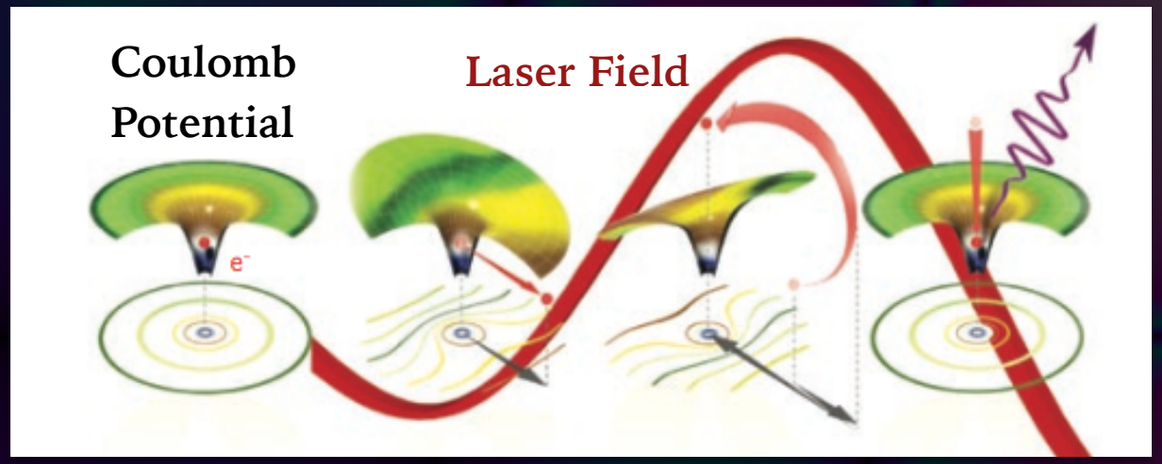


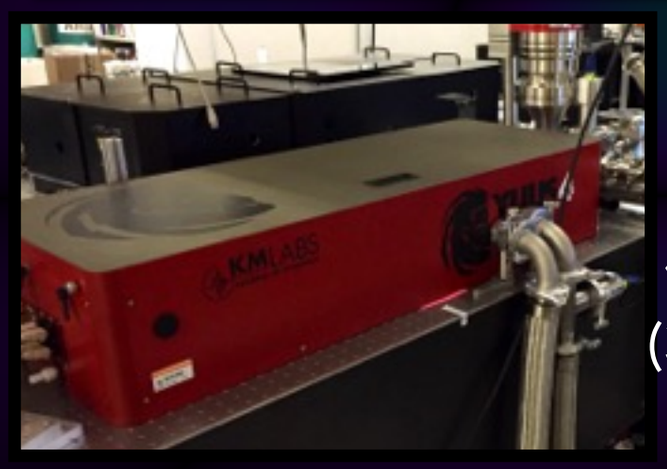
Tabletop EUV Microscopes: Coherent HHG Source + Lensless Imaging

High Harmonic Generation

Input:
800 nm, 3 mJ,
3 kHz Ti:Sapph,
38 fs pulses





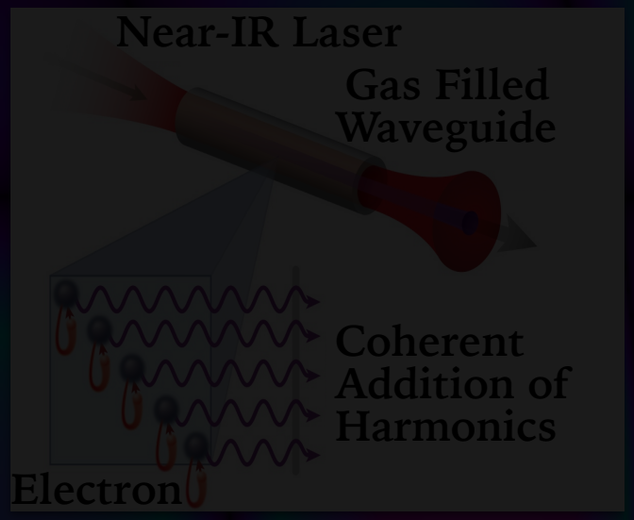


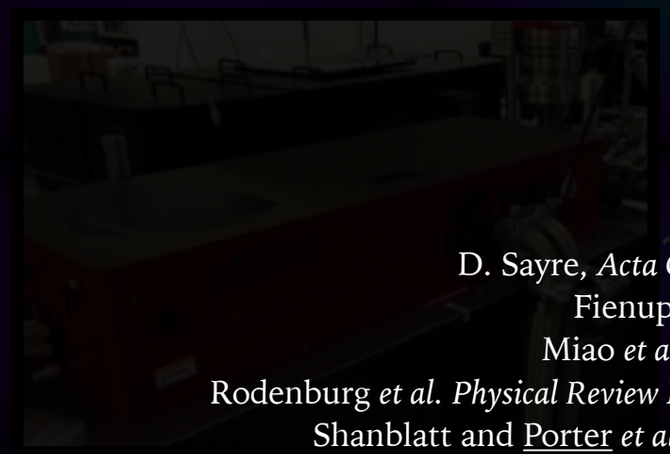
Output: Coherent Ultrafast pulses
~500nW @ 13nm
(3.25 x 10^{10} ph/s)

McPherson *et al.*, *JOSA B* **4**, 595 (1987)
Rundquist *et al.*, *Science* **280**, 1412 (1998)
Bartels *et al.*, *Science* **297**, 376 (2002)
Zhang *et al.*, *Optics Letters* **29**, 1357 (2004)

Tabletop EUV Microscopes: Coherent HHG Source + Lensless Imaging

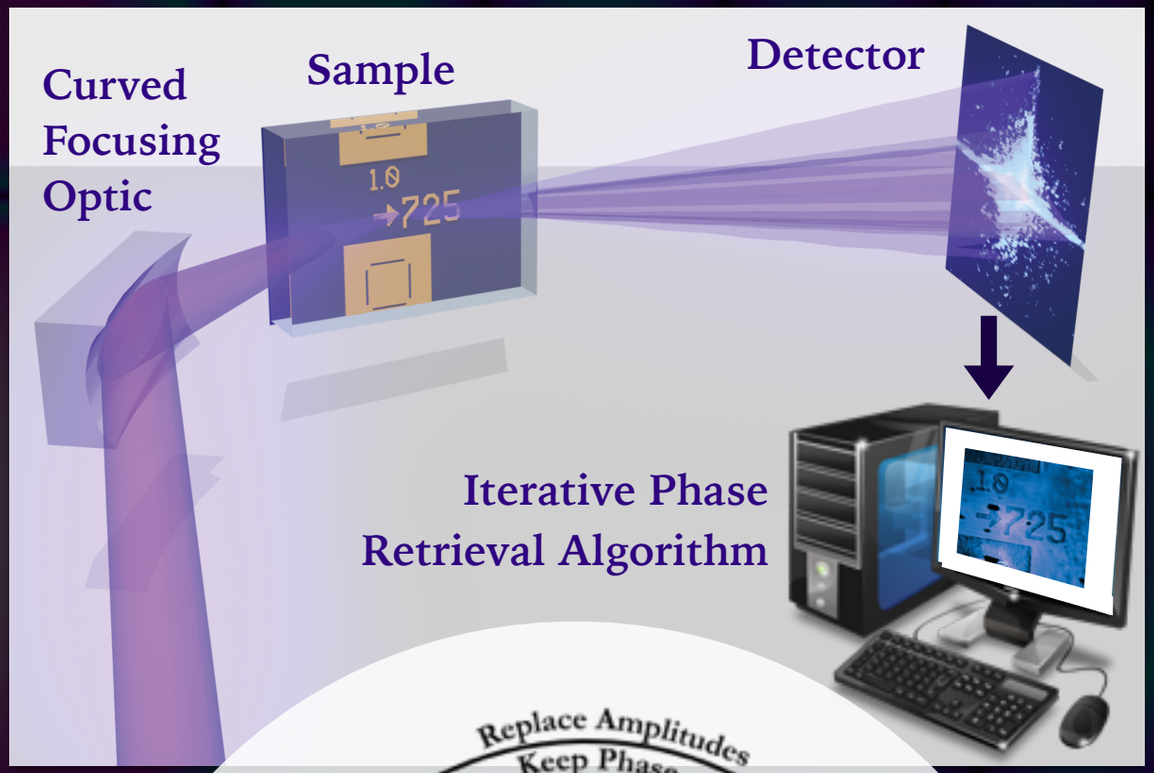
High Harmonic Generation

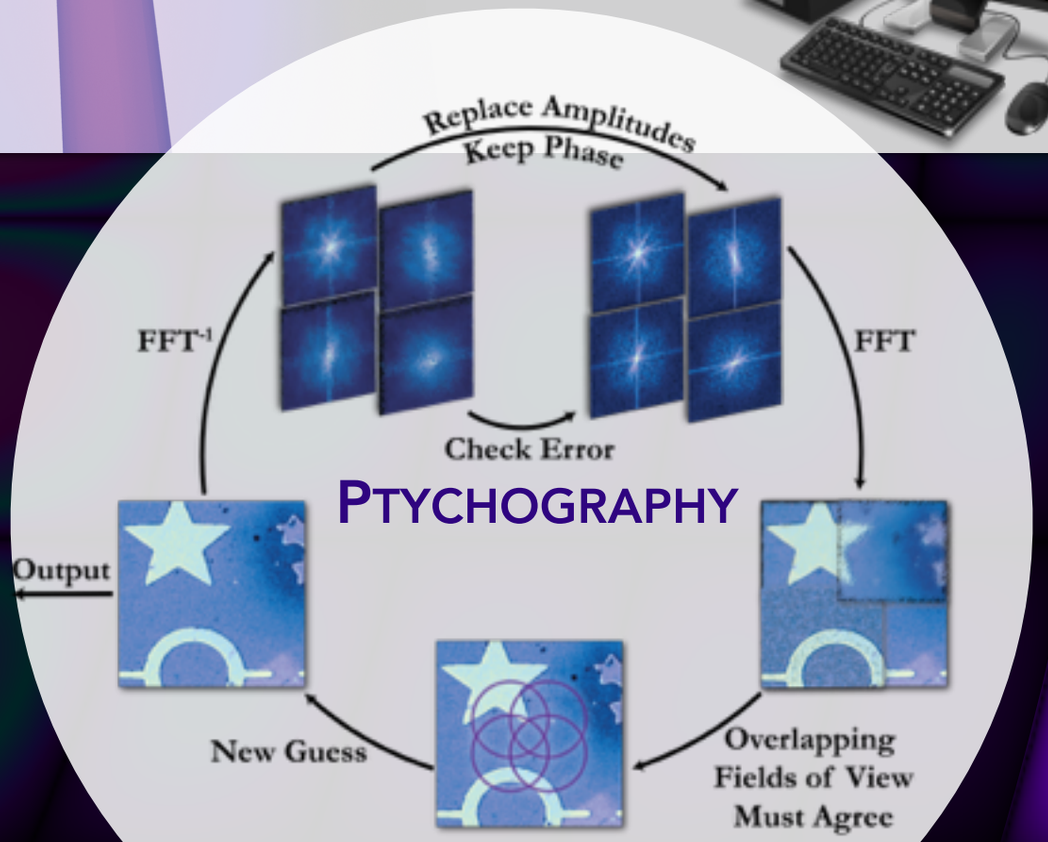




Coherent
Ultrafast pulses
~500nW @ 13nm

Coherent Diffractive Imaging

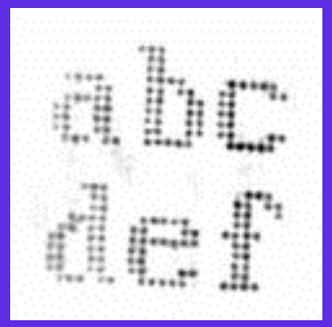




D. Sayre, *Acta Crystallography* **5**, 843 (1952)
Fienup, *Optics Letters* **3**, 27 (1978)
Miao *et al.*, *Nature*, 400, 342 (1999)
Rodenburg *et al. Physical Review Letters* **98**, 034801 (2007)
Shanblatt and Porter *et al.*, *Nano Letters* **16** (2016)

Advances in Image Quality using HHG CDI

1999: First X-ray CDI

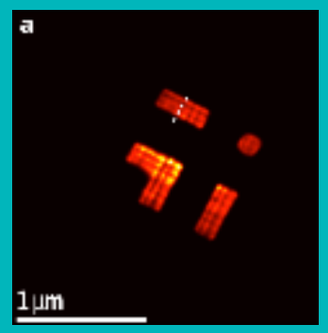


Nature **400**, 6747 (1999)

2007: First HHG CDI

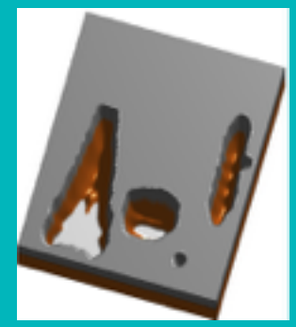
PRL **99**, 9 (2007)

2011: 22 nm resolution



Opt. Ex. **19**, 22470 (2011)

2013: Semi-transparent

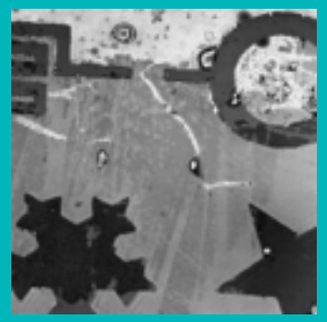


Opt. Ex. **21**, 19 (2013)

2014: First reflection

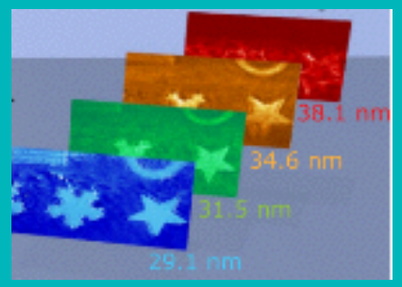
Optica **1**, 1 (2014)

2015: High NA reflection



Ultramicroscopy **158**, 98 (2015)

2016: Hyperspectral

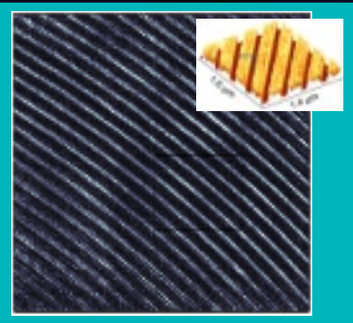


Opt. Ex. **24**, 16 (2016)

2016: Quant. buried layer

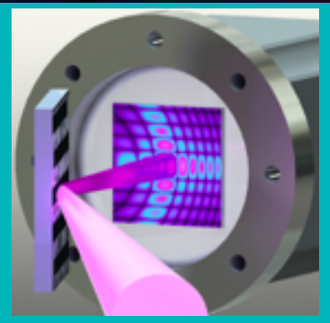
Nano Lett. **16**, 5444 (2016)

2017: 1st sub-λ, periodic



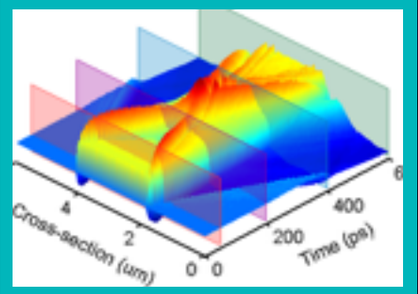
Nat. Photon. **11**, 22 (2017)
OPN Optics in 2017

2017: 13nm reflection



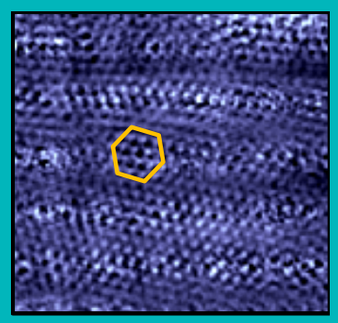
Optica ***4****, 1552 (2017)*

2018: Dynamic imaging



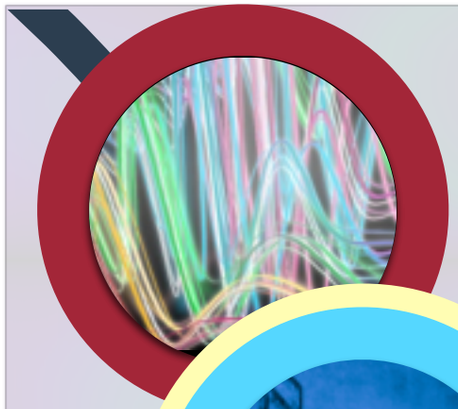
Postdeadline paper, CLEO (2017)
Submitted. (2018)

2018: Colloids, large FOV



Ultramicroscopy ***184****, 164 (2018)*
Opt. Express **26**, *11393 (2018)*

Presentation Outline



01 - INTRODUCTION

02 - 30NM BURIED LAYER IMAGING

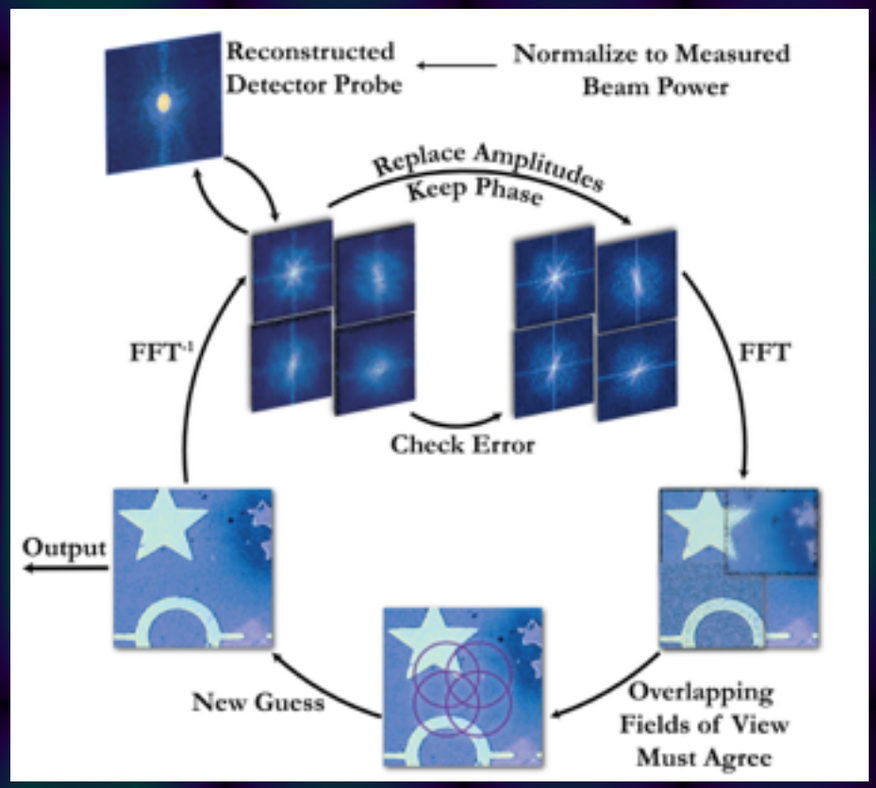
03 - 13NM TRANSMISSION IMAGING

04 - 13NM REFLECTION IMAGING

05 - 13NM COMPLEX IMAGING REFLECTOMETRY

Quantitative Buried Layer Imaging at 30nm

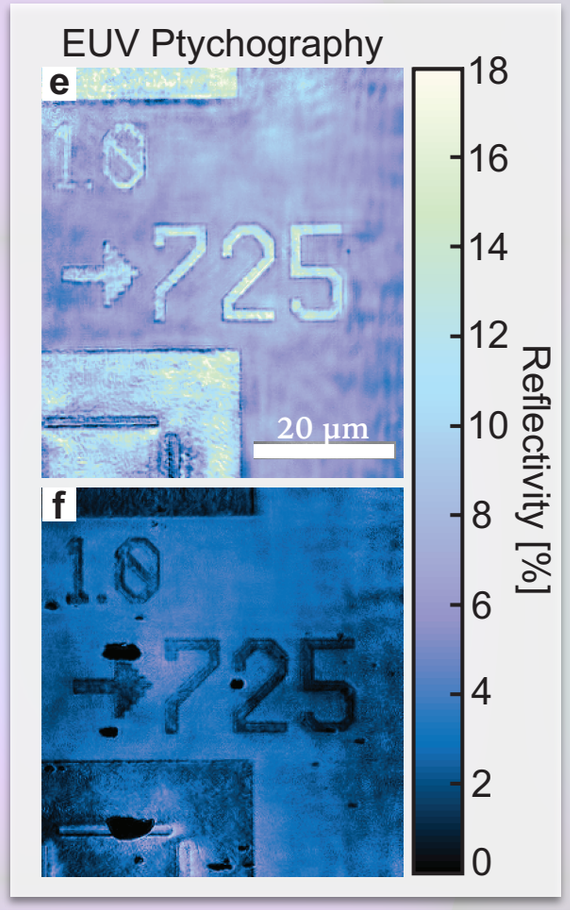
RAPTR CDI

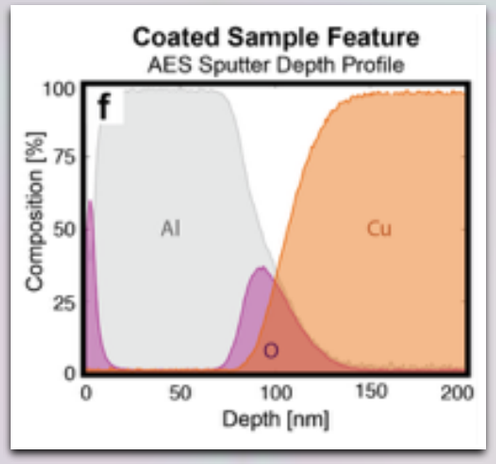


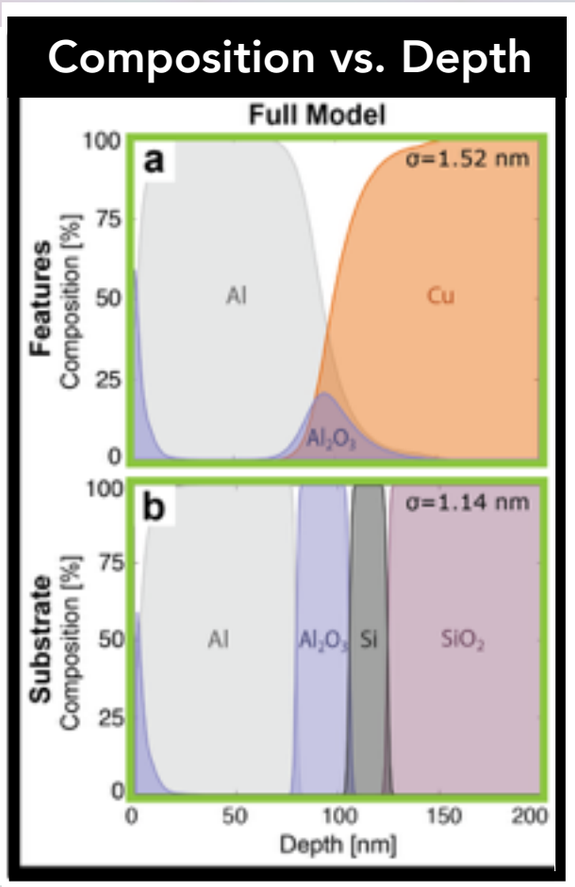
Quantitative imaging of a buried interface utilizing transparency of Al to 30nm light

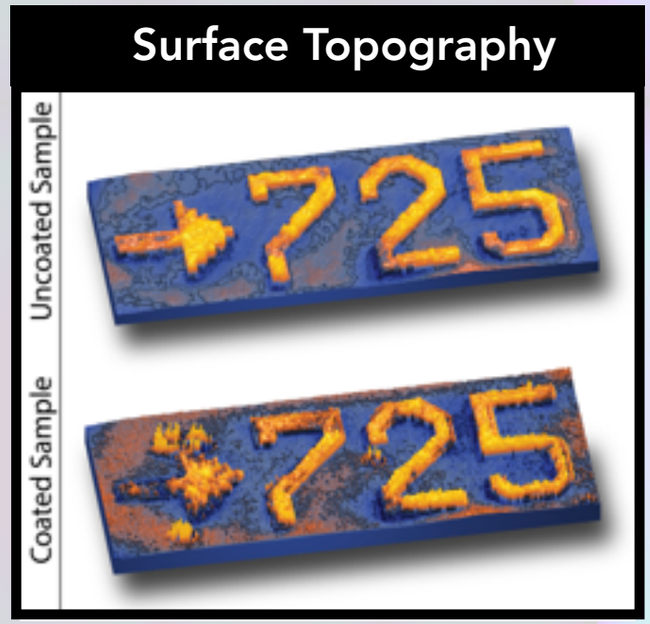
Shanblatt and Porter *et al.*, *Nano Letters* **16** (2016)

Quantitative Buried Layer Imaging at 30nm









With an EUV ptychography image and auger electron spectroscopy info, we could deduce surface topography & spatially-resolved composition vs. depth

Can we design a standalone EUV microscope that solves for composition vs. depth?

Presentation Outline

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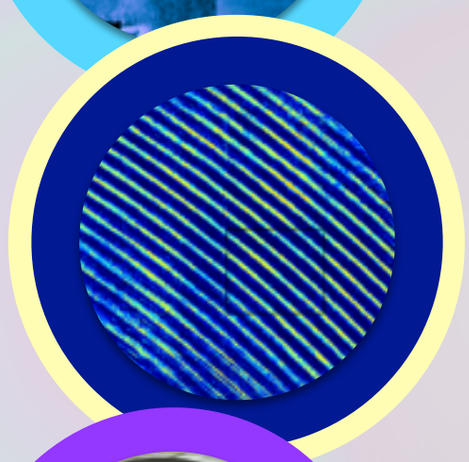
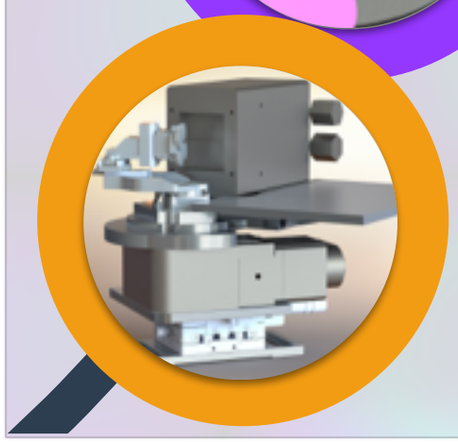
02 - 30NM BURIED LAYER IMAGING



03 - 13NM TRANSMISSION IMAGING

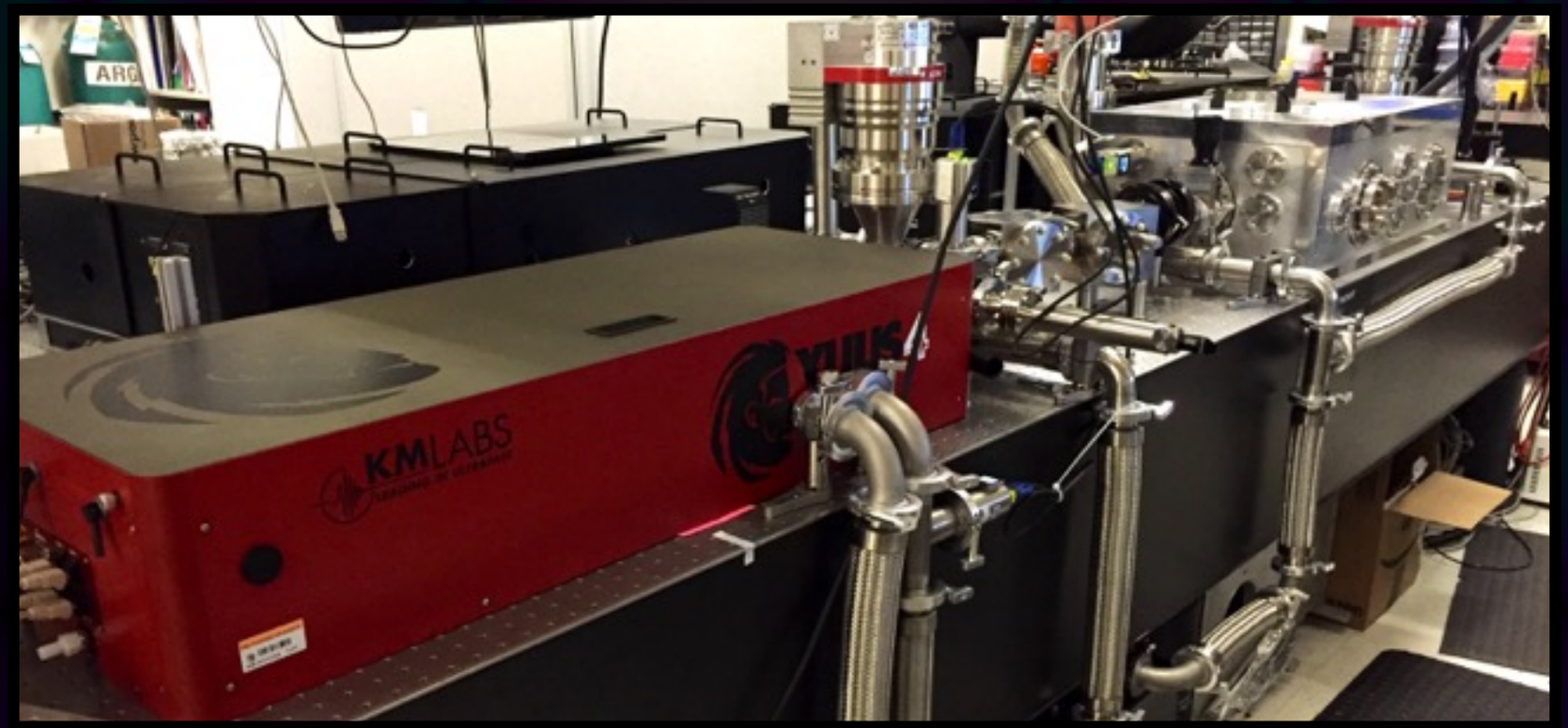
04 - 13NM REFLECTION IMAGING



05 - 13NM COMPLEX IMAGING REFLECTOMETRY

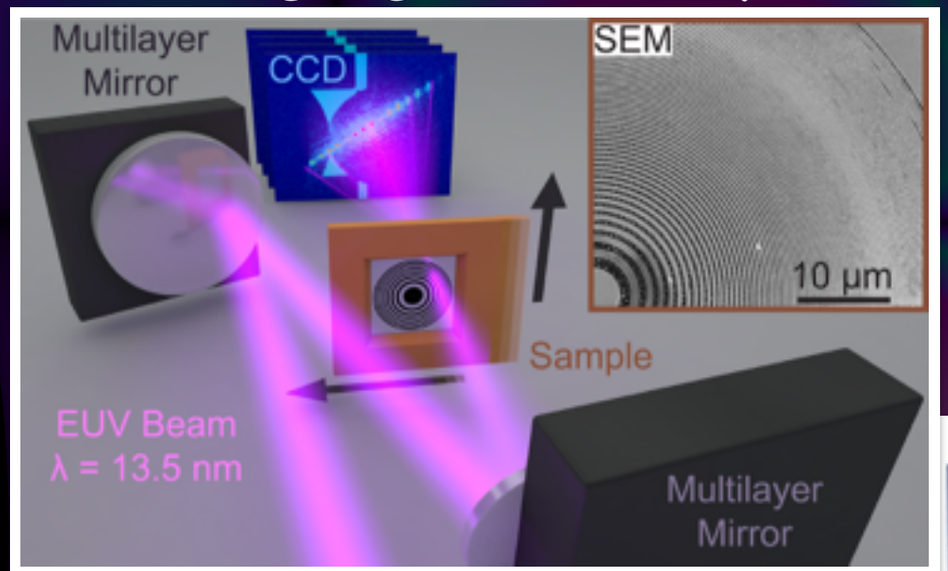
Previous work used λ = 30 nm…

Recently: We've built 2 new microscopes for transmission & reflection-mode imaging at λ = 13 nm for higher resolution, actinic inspection, & quantitative applications.

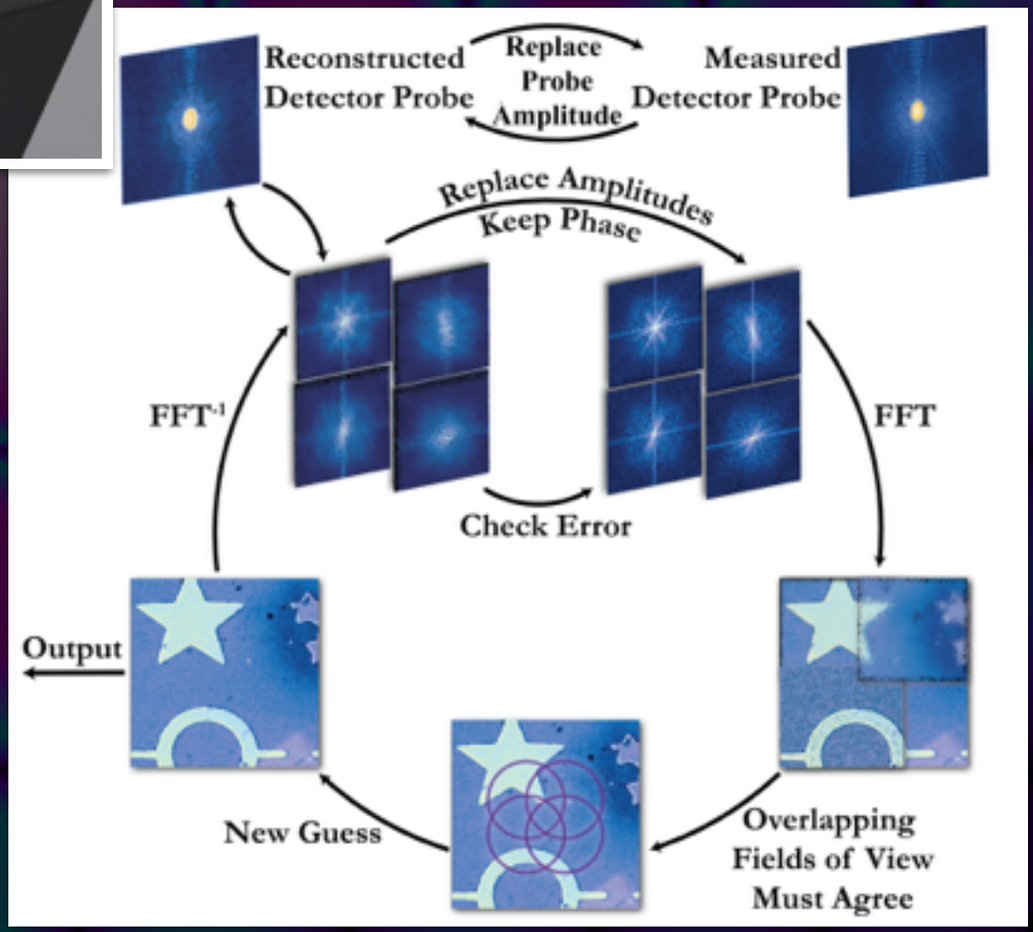


Record Resolution λ=13.5 nm Transmission-Mode Results

Imaging Geometry:



Reconstruction: Modulus Enforced Probe

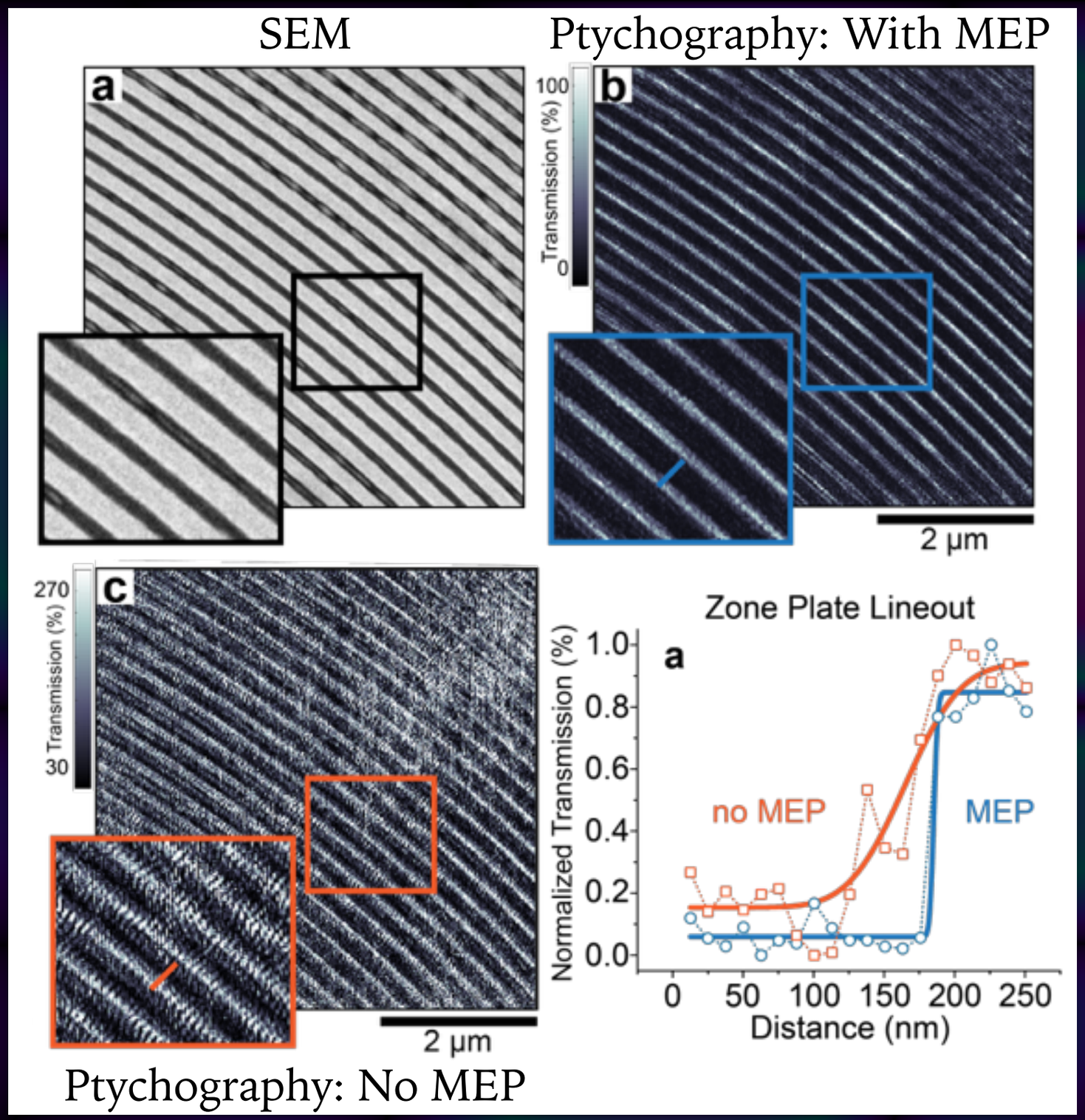


MEP + Ptychography:
Improved Convergence
Compatible with RAPTR CDI (returns absolute transmissivity/reflectivity)

Gardner *et al.*, *Nature Photonics* (March 2017), doi:10.1038/nphoton.2017.33.

"Modulus-Enforced Probe," PCT/US Patent Application 17/33397 (2016).

Record Resolution λ=13.5 nm Transmission-Mode Results

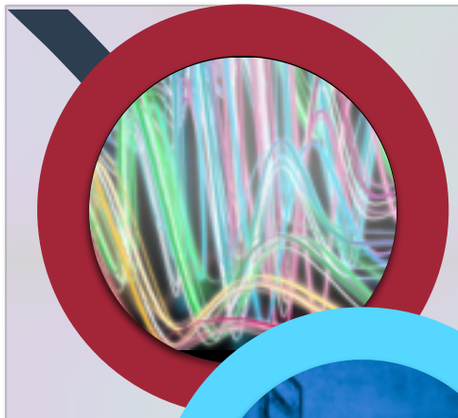


With MEP, lineouts and power spectral density support **12.6 nm resolution**

This is the **1st full-field, sub-wavelength EUV CDI** to date.

Gardner *et al.*, *Nature Photonics* (March 2017), doi:10.1038/nphoton.2017.33. "Modulus-Enforced Probe," PCT/US Patent Application 17/33397 (2016).

PRESENTATION OUTLINE



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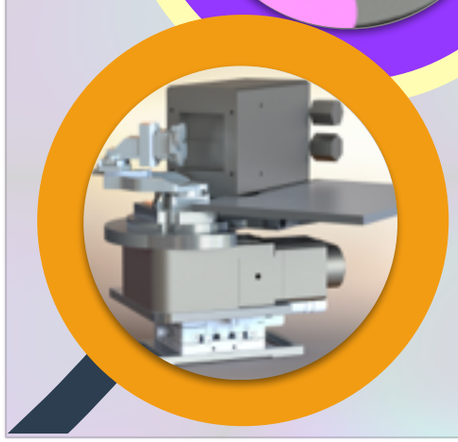
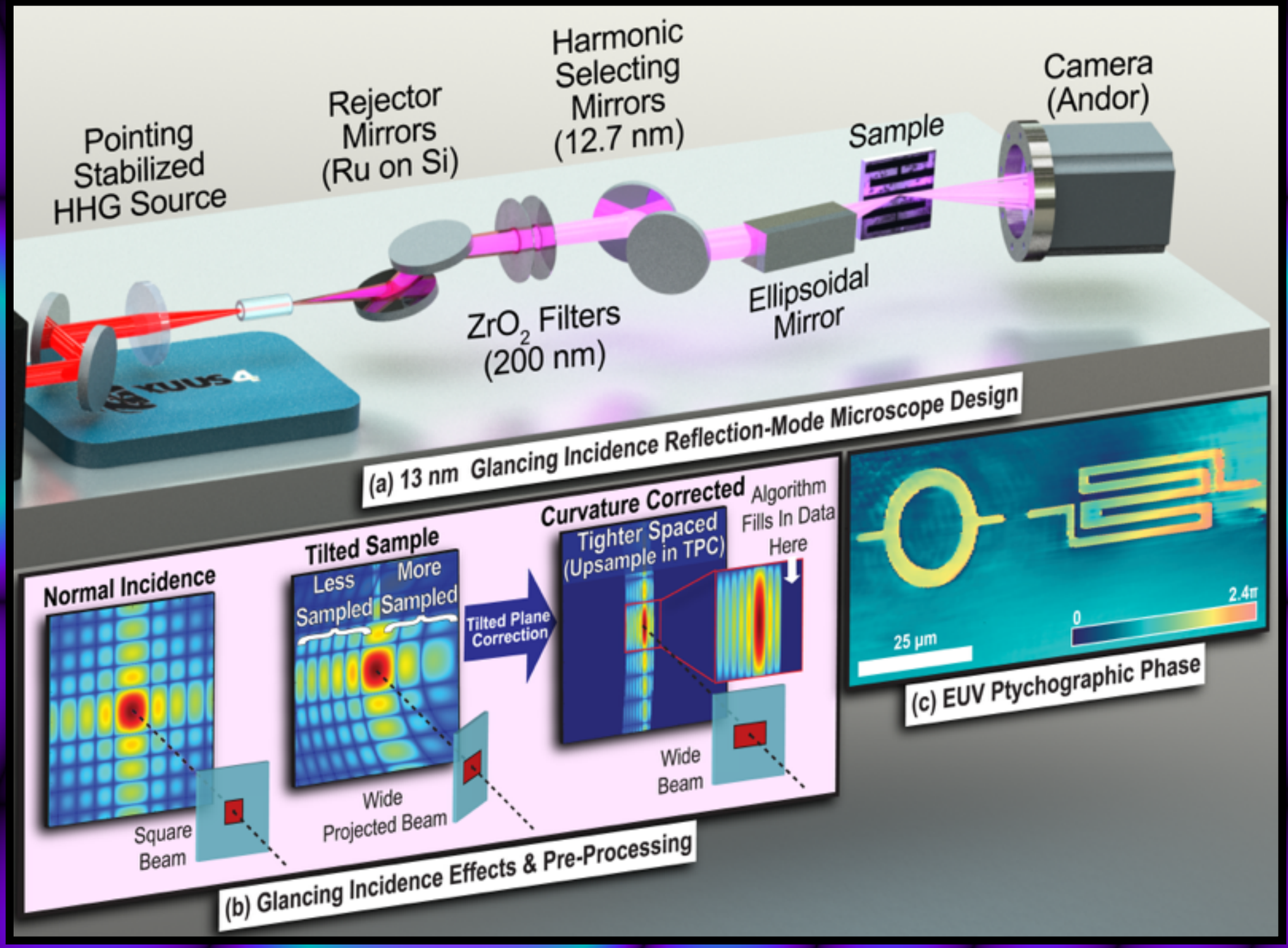


04 - 13NM REFLECTION IMAGING

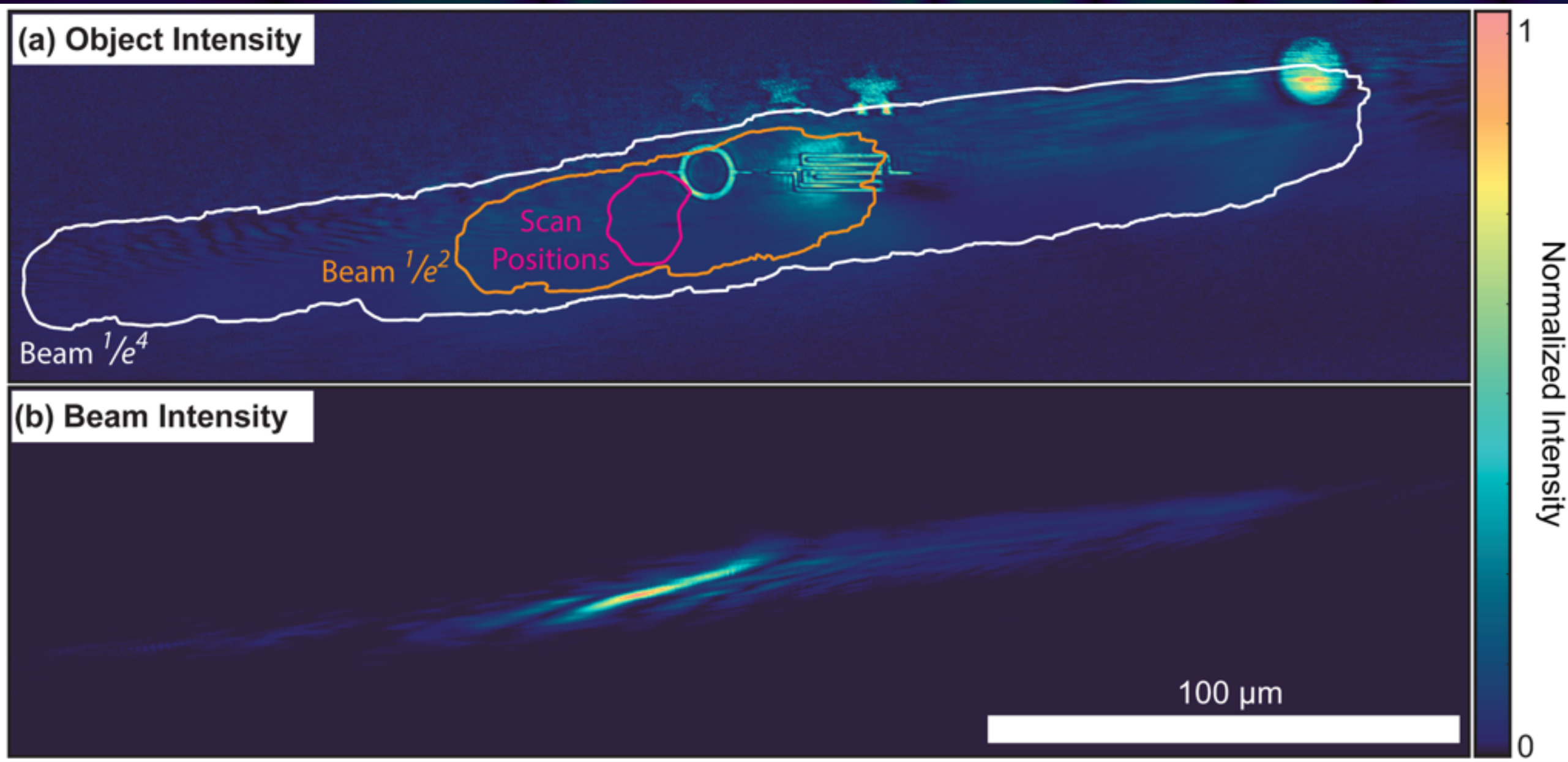
05 - 13NM COMPLEX IMAGING REFLECTOMETRY

First Tabletop 13nm Reflection Imaging

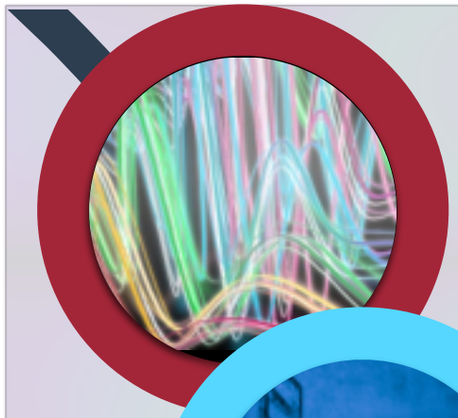


Porter and Tanksalvala *et al.*, *Optica* **4** (2017).

First Tabletop 13nm Reflection Imaging



PRESENTATION OUTLINE



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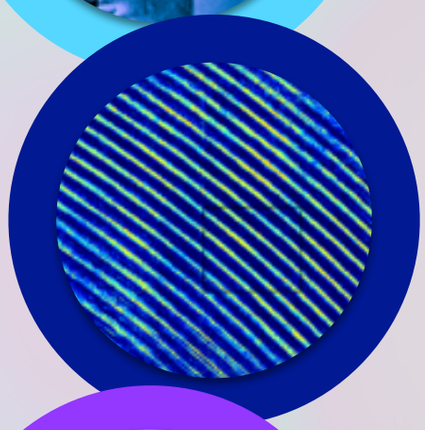


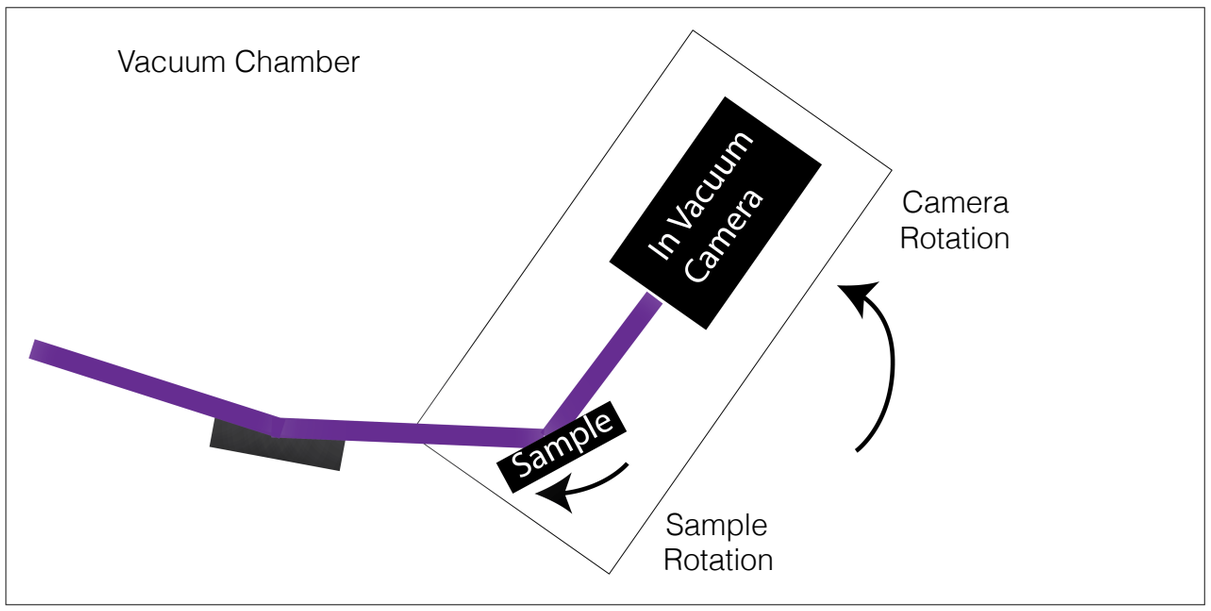
03 - 13NM TRANSMISSION IMAGING

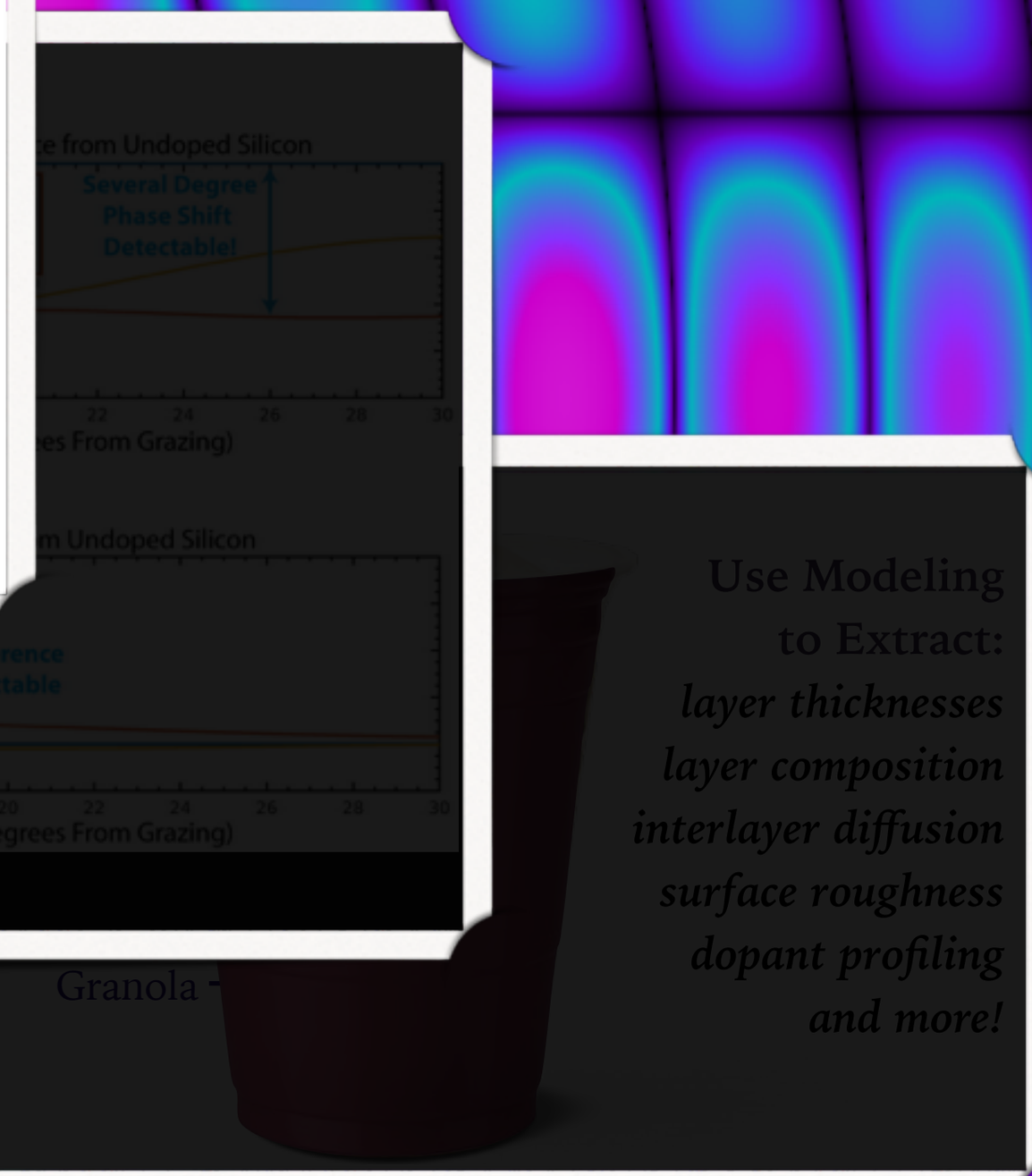
04 - 13NM REFLECTION IMAGING

05 - 13NM COMPLEX IMAGING REFLECTOMETRY

Current Work: 13nm Complex Imaging Reflectometry

Perform ptychographic 13nm imaging at many incidence angles.





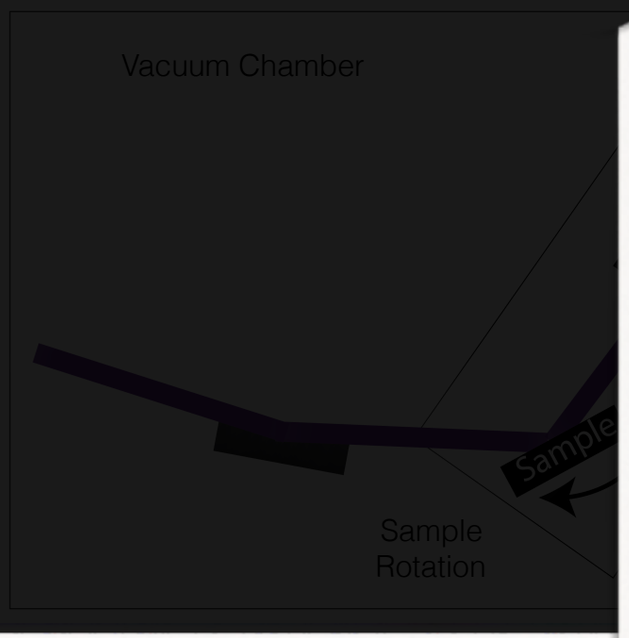
Use Modeling to Extract:

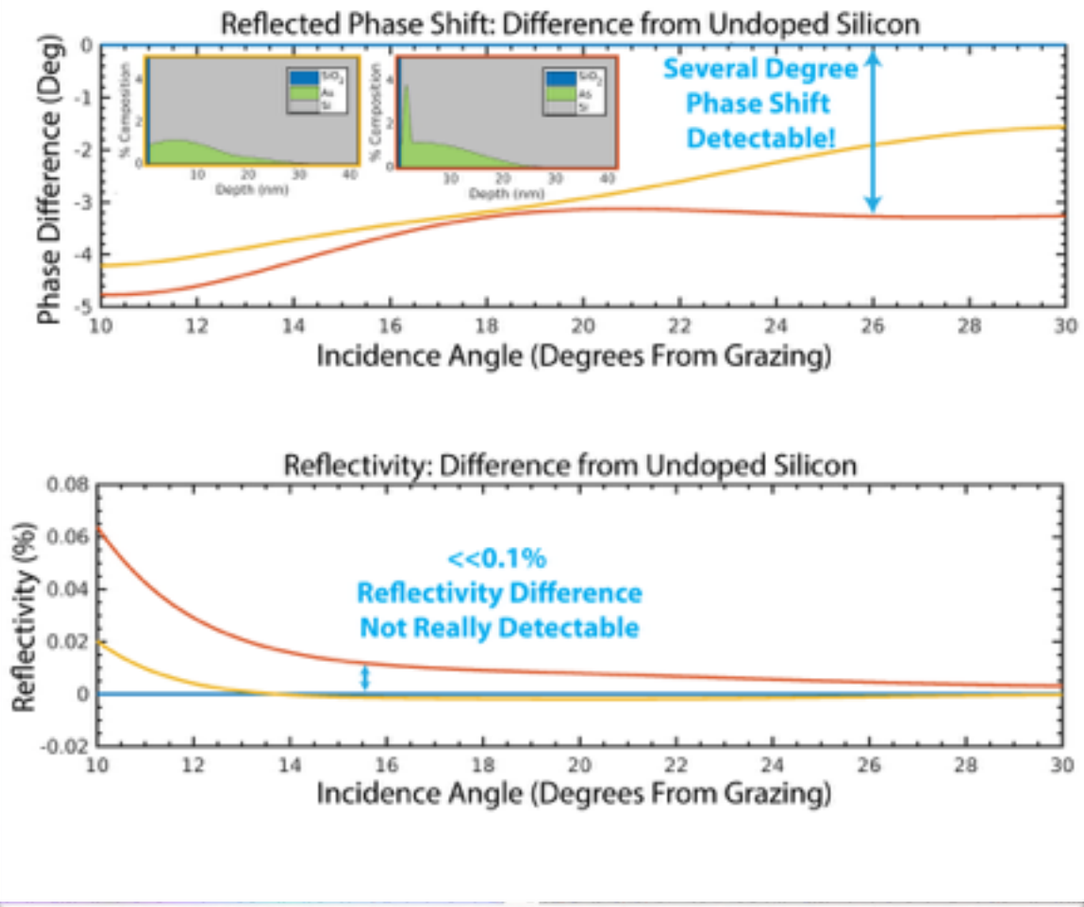
layer thicknesses
layer composition
interlayer diffusion
surface roughness
dopant profiling
and more!

C. Porter, D. Adams, M. Tanksalvala, E. Shanblatt, M. Murnane, H. Kapteyn, "Complex Spatially-Resolved Reflectometry/Refractometry," PCT/US Patent Application 17/33404 (2016).

Current Work: 13nm Complex Imaging Reflectometry

Perform ptychographic 13nm imaging at many incidence angles





Granola -

Use Modeling to Extract:

layer thicknesses
layer composition
interlayer diffusion
surface roughness
dopant profiling
and more!

C. Porter, D. Adams, M. Tanksalvala, E. Shanblatt, M. Murnane, H. Kapteyn, "Complex Spatially-Resolved Reflectometry/Refractometry," PCT/US Patent Application 17/33404 (2016).

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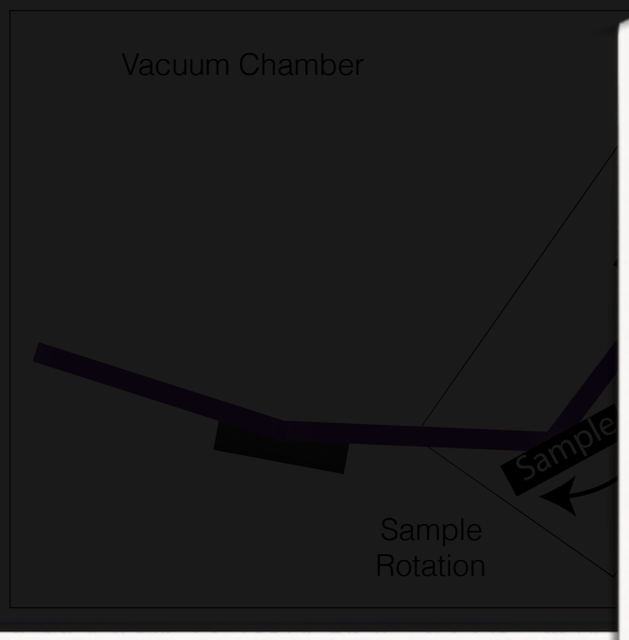

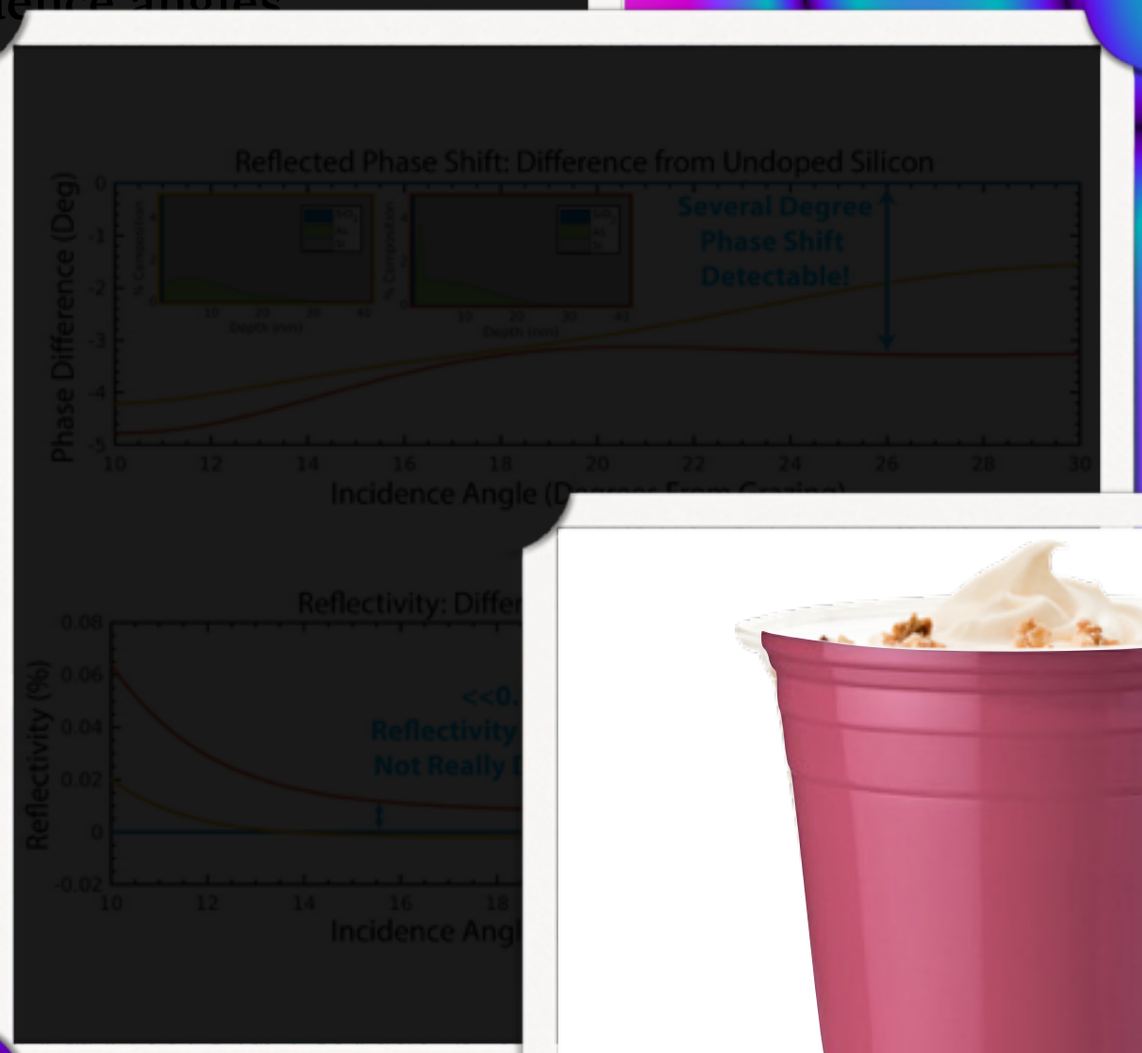

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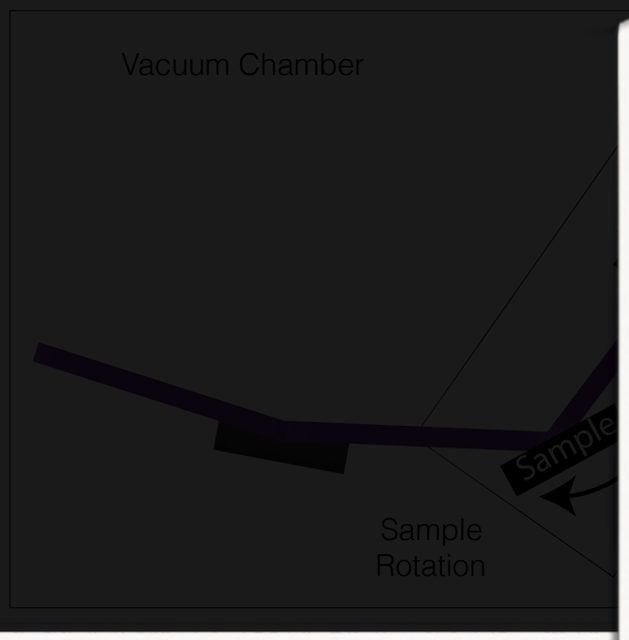

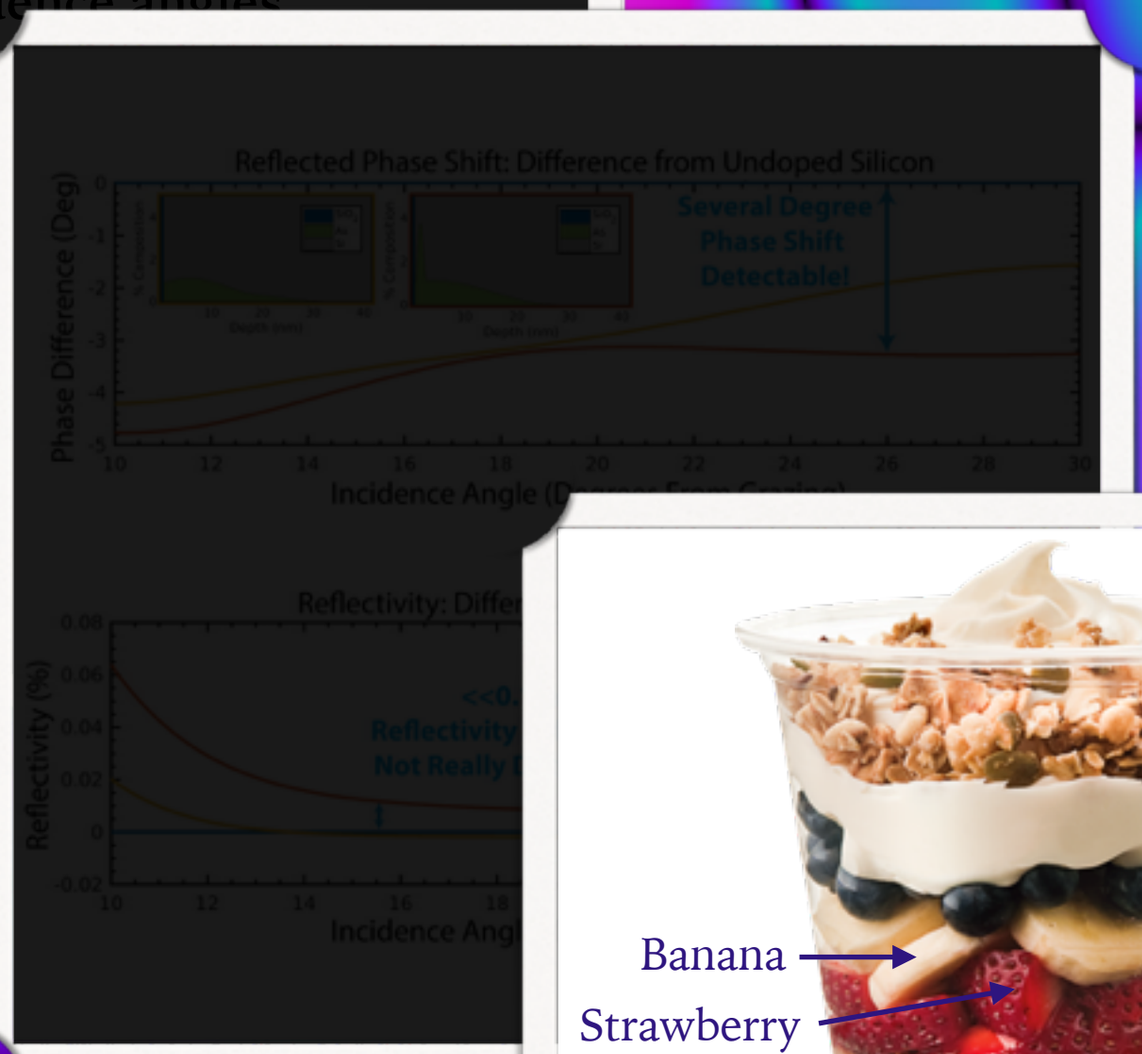

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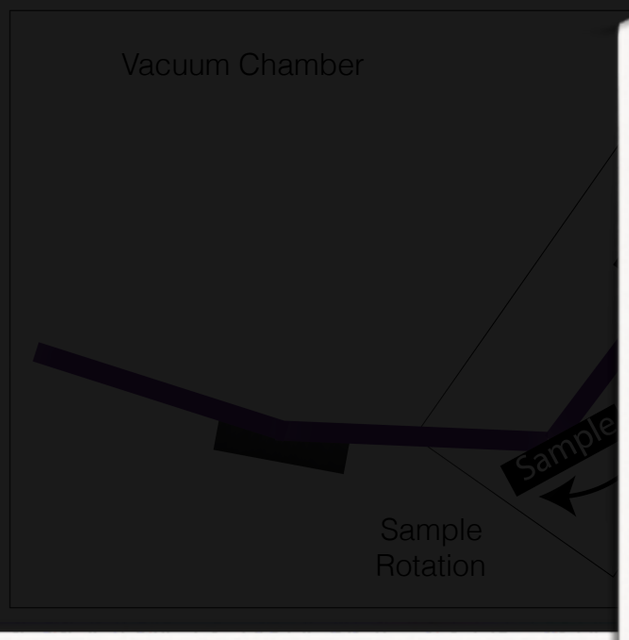

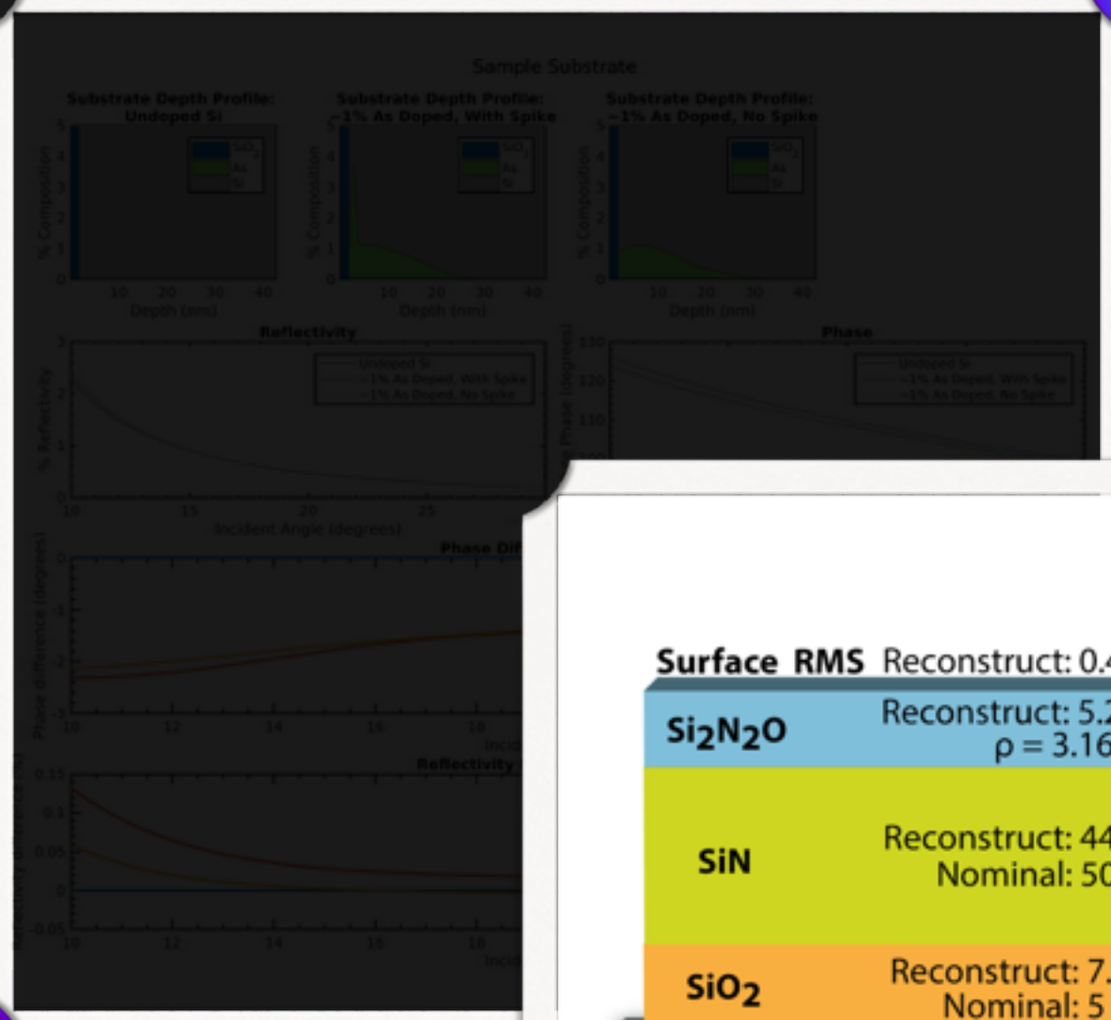

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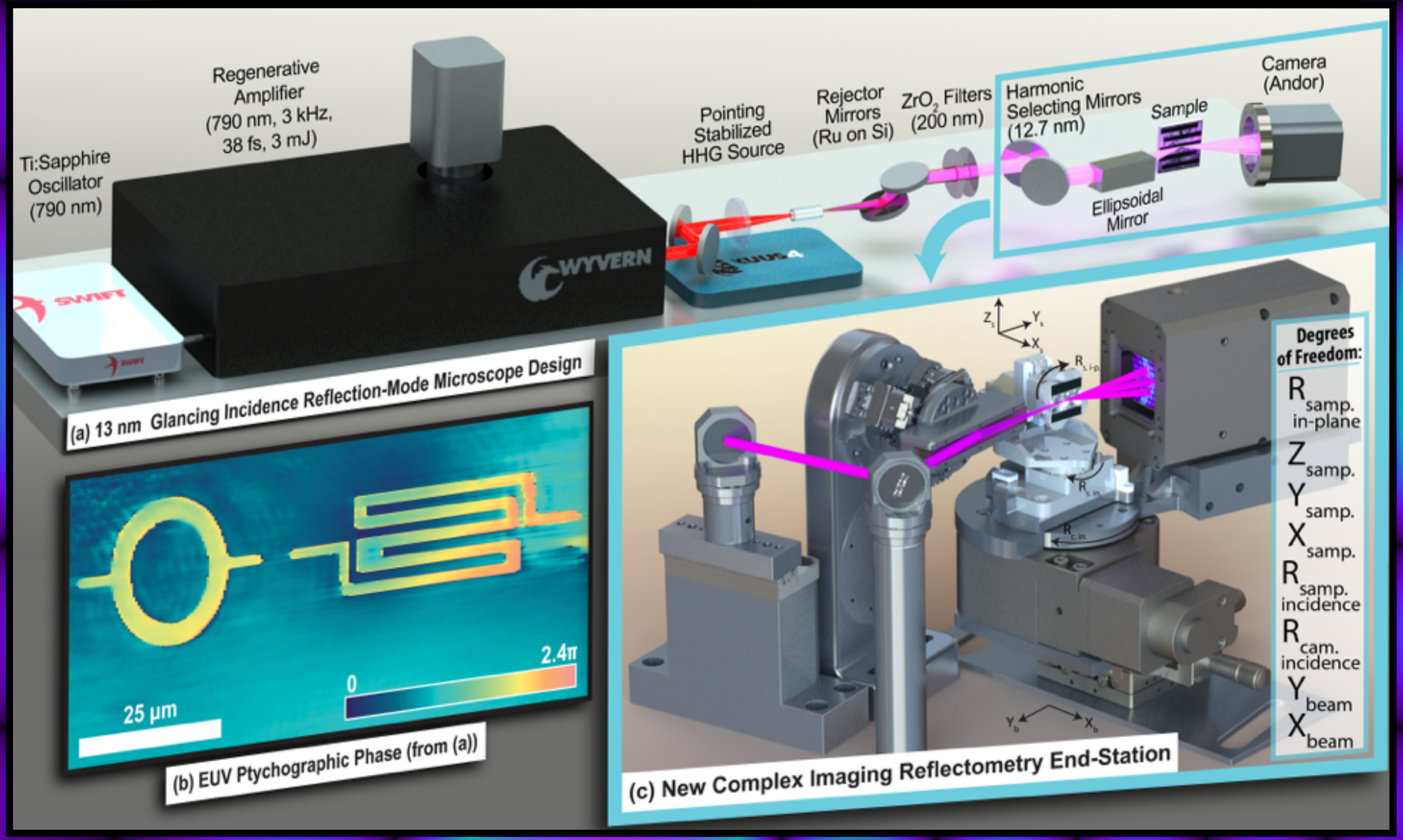
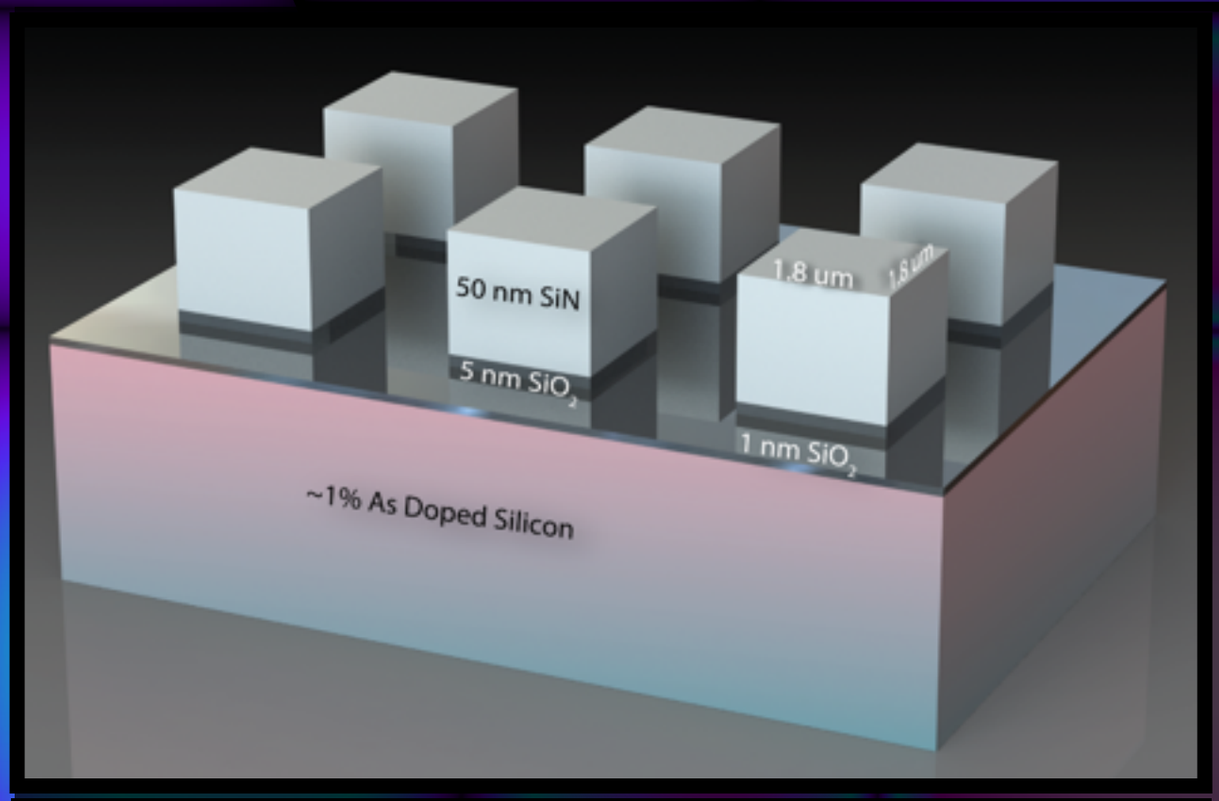
13nm Reflection Microscope → Imaging Reflectometer

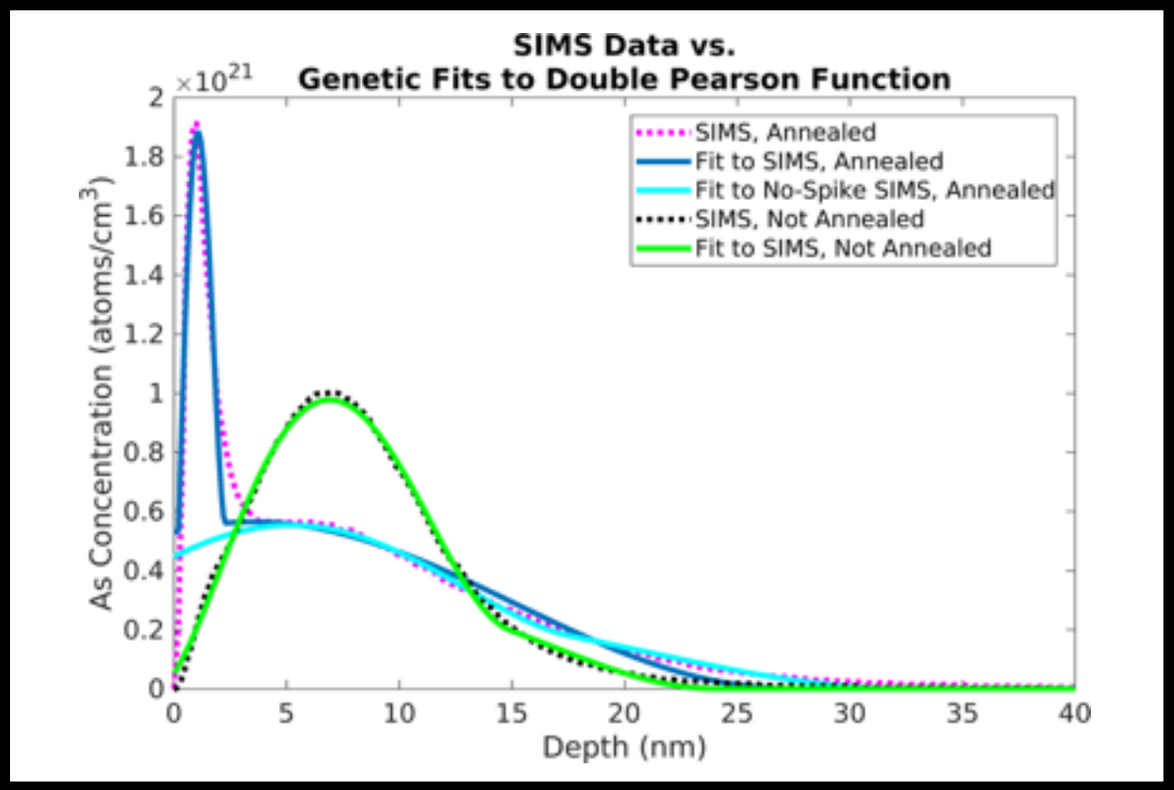


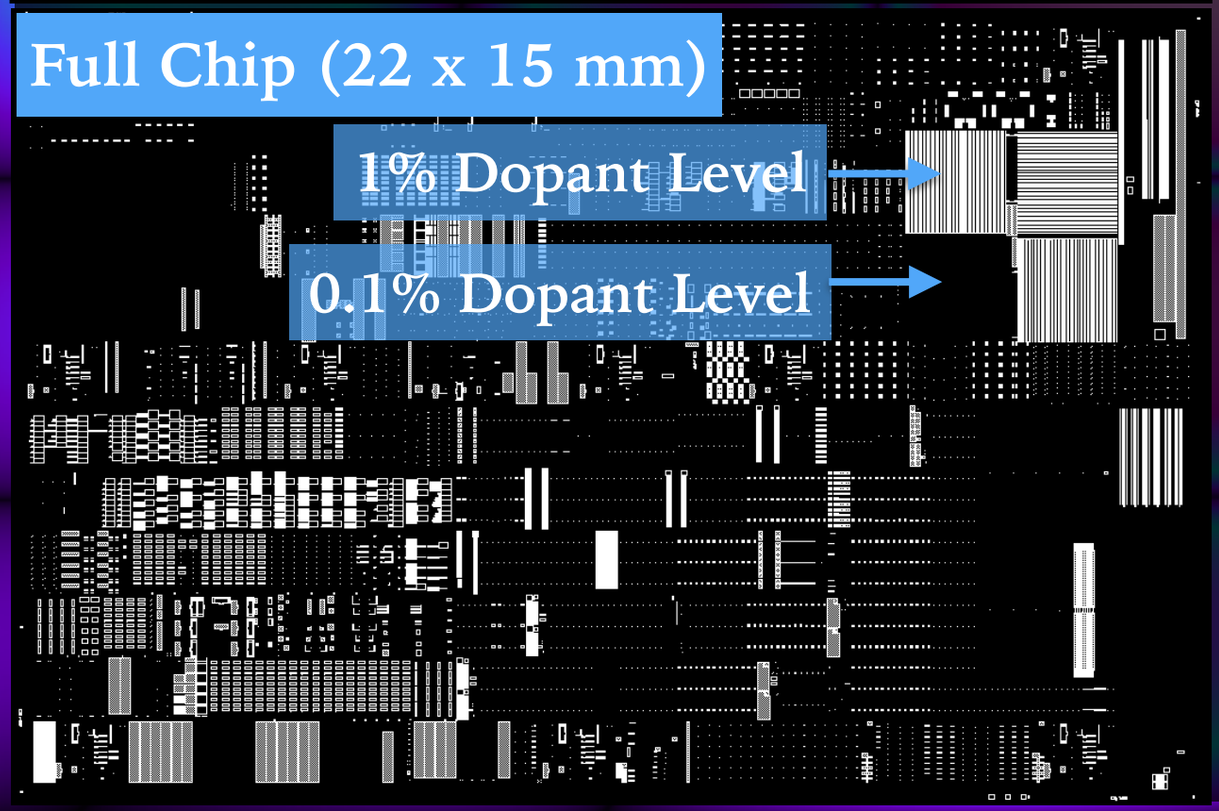
Porter and Tanksalvala *et al.*, Proc. SPIE Vol. 10585, Metrology, Inspection, and Process Control for Microlithography XXXII; 105850M (2018).

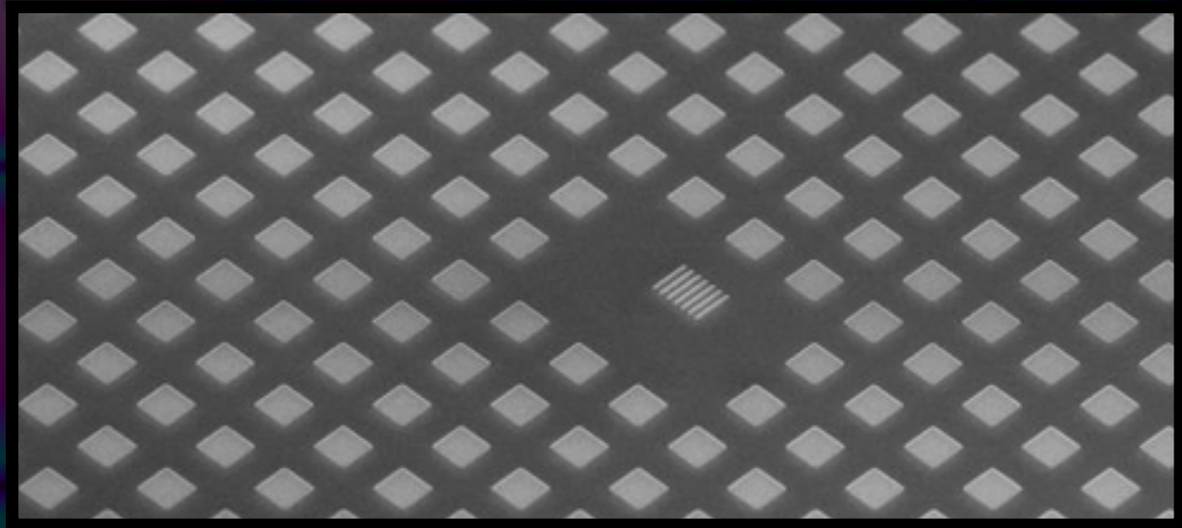
C. Porter, D. Adams, M. Tanksalvala, E. Shanblatt, M. Murnane, H. Kapteyn, "Complex Spatially-Resolved Reflectometry/Refractometry," PCT/US Patent Application 17/33404 (2016).

First Imaging Reflectometry Sample



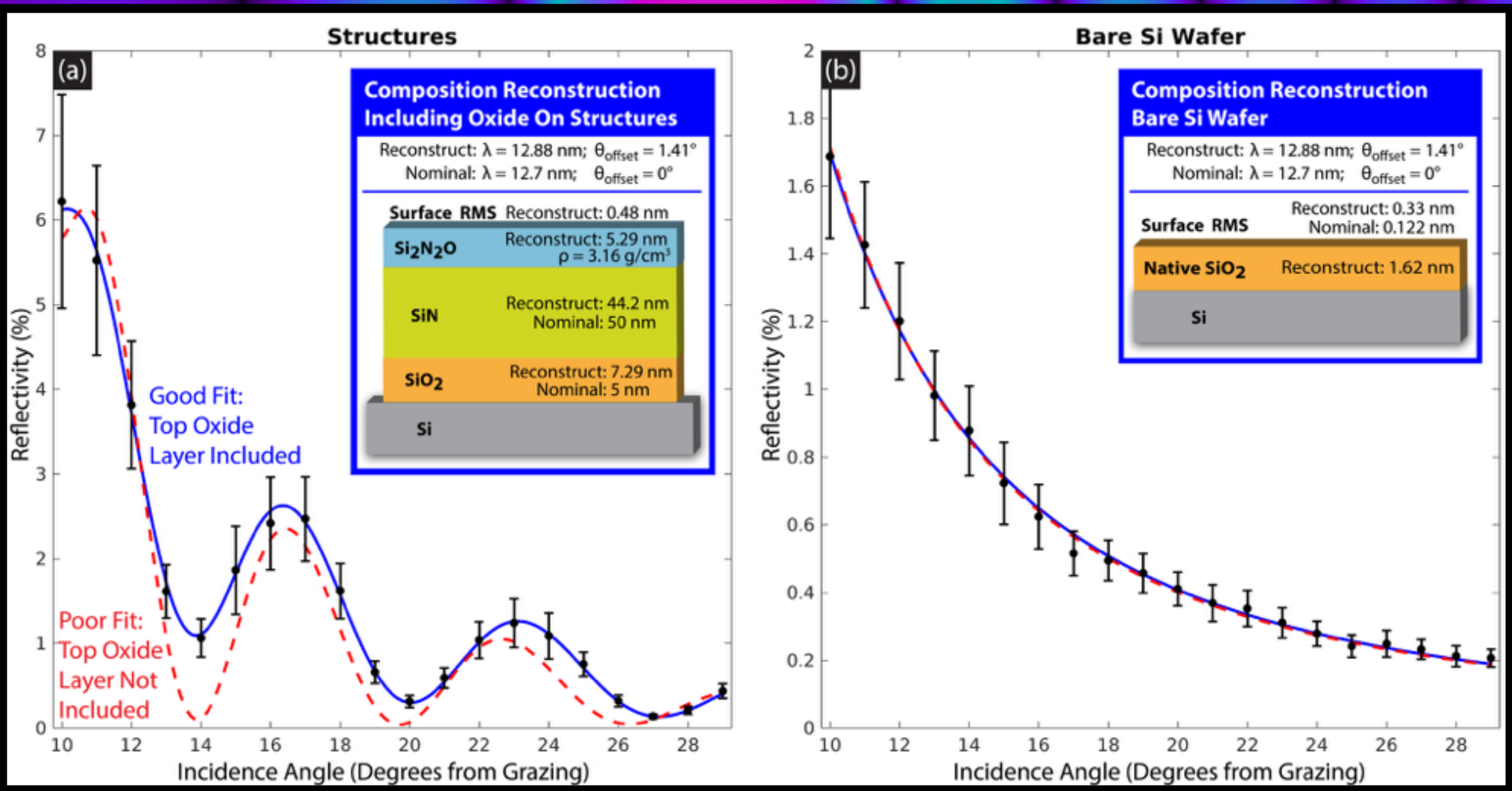






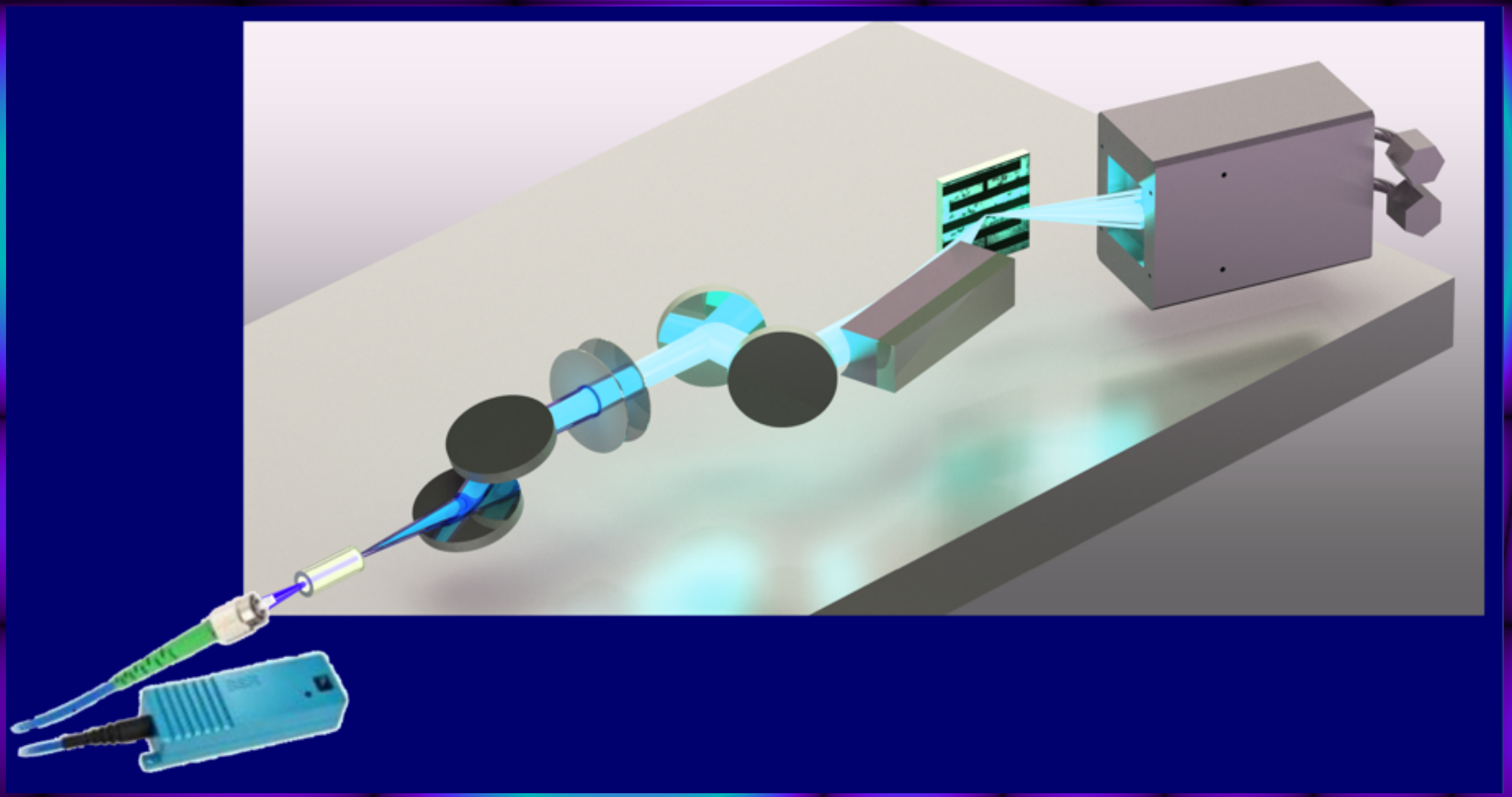
As-Doped Si Sample from imec:
Measure Dopant Concentration vs Depth

First 13nm Experiment: Non-Imaging Reflectometry



System Verification: Imaging with 450nm Light

Goal: Confirm all imaging hardware and software functionality by sending 450nm light from fiber coupled laser diode through imaging reflectometer.



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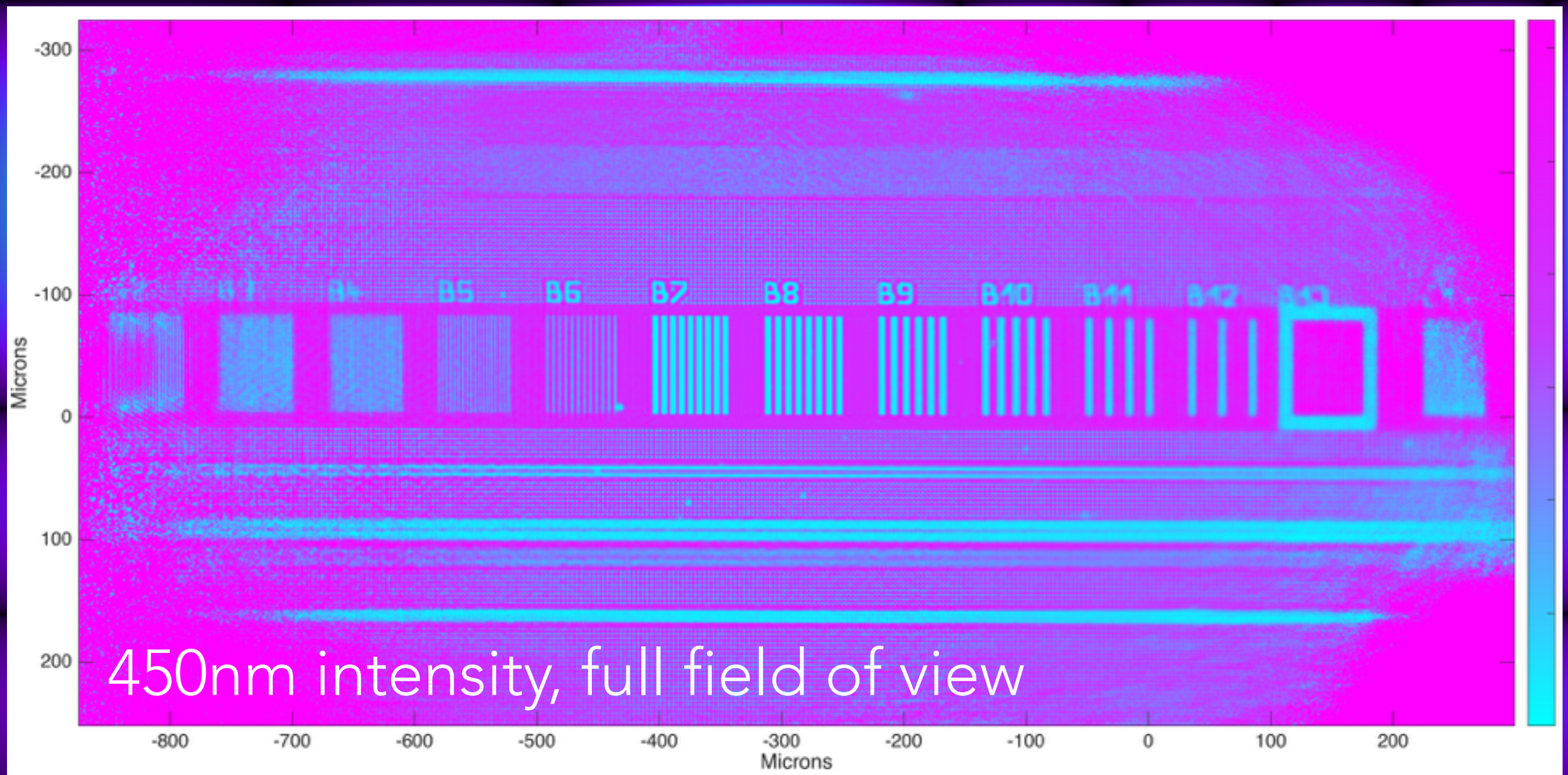

450nm intensity, full field of view

Results in preparation.

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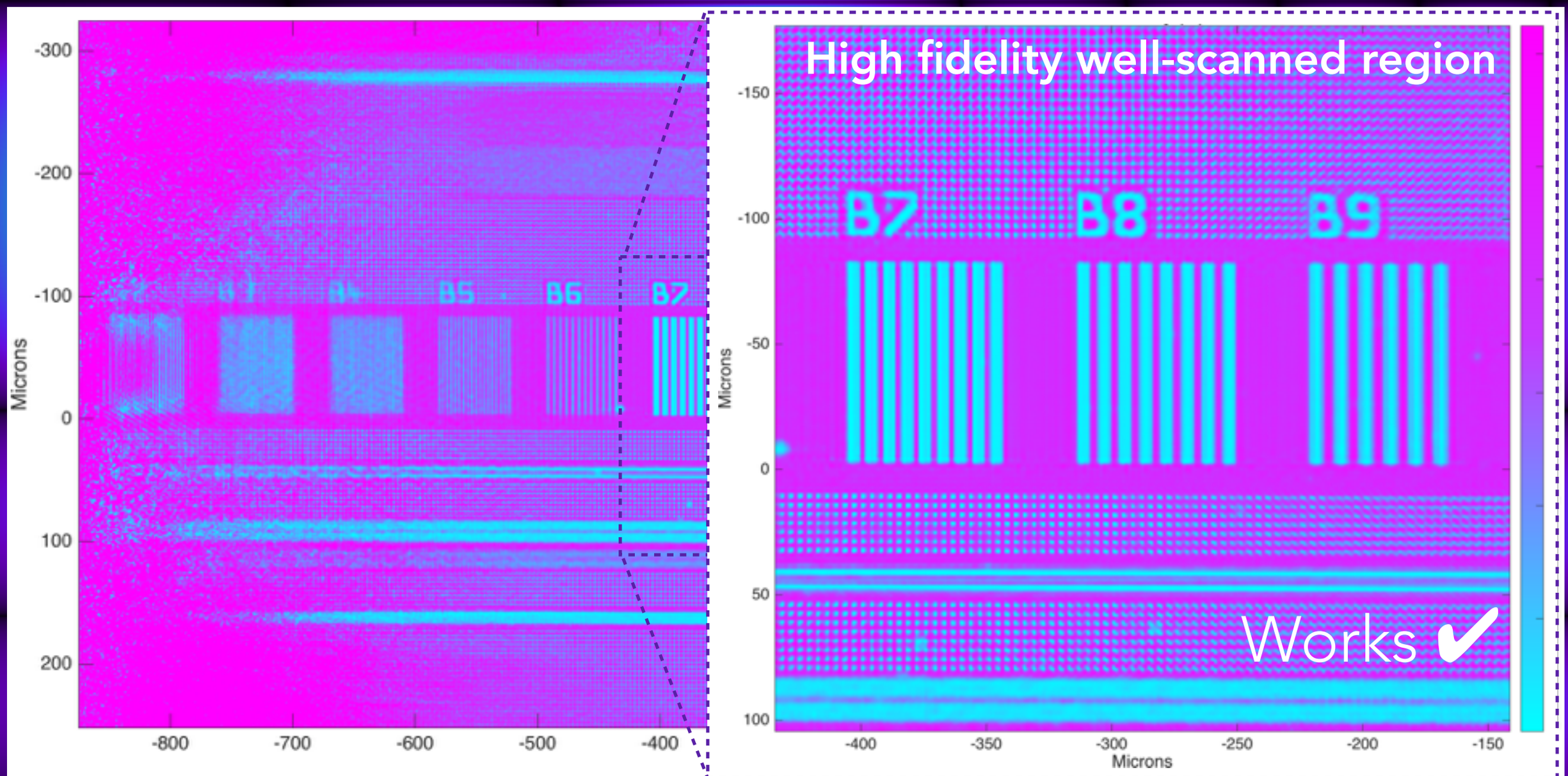

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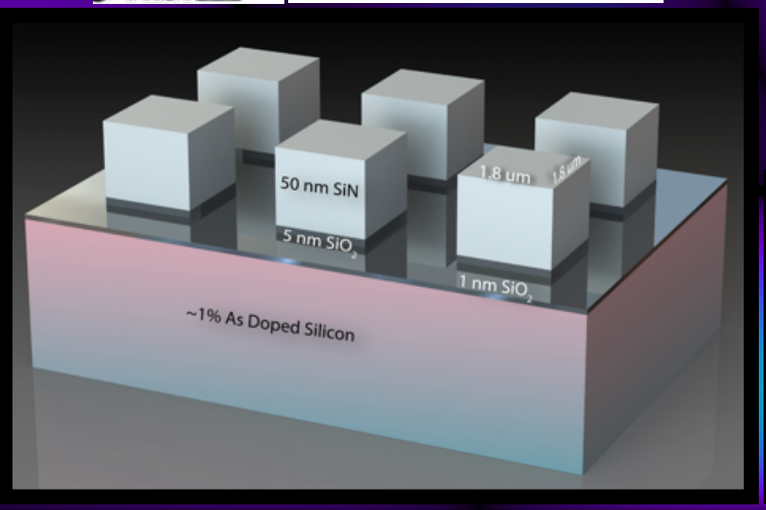
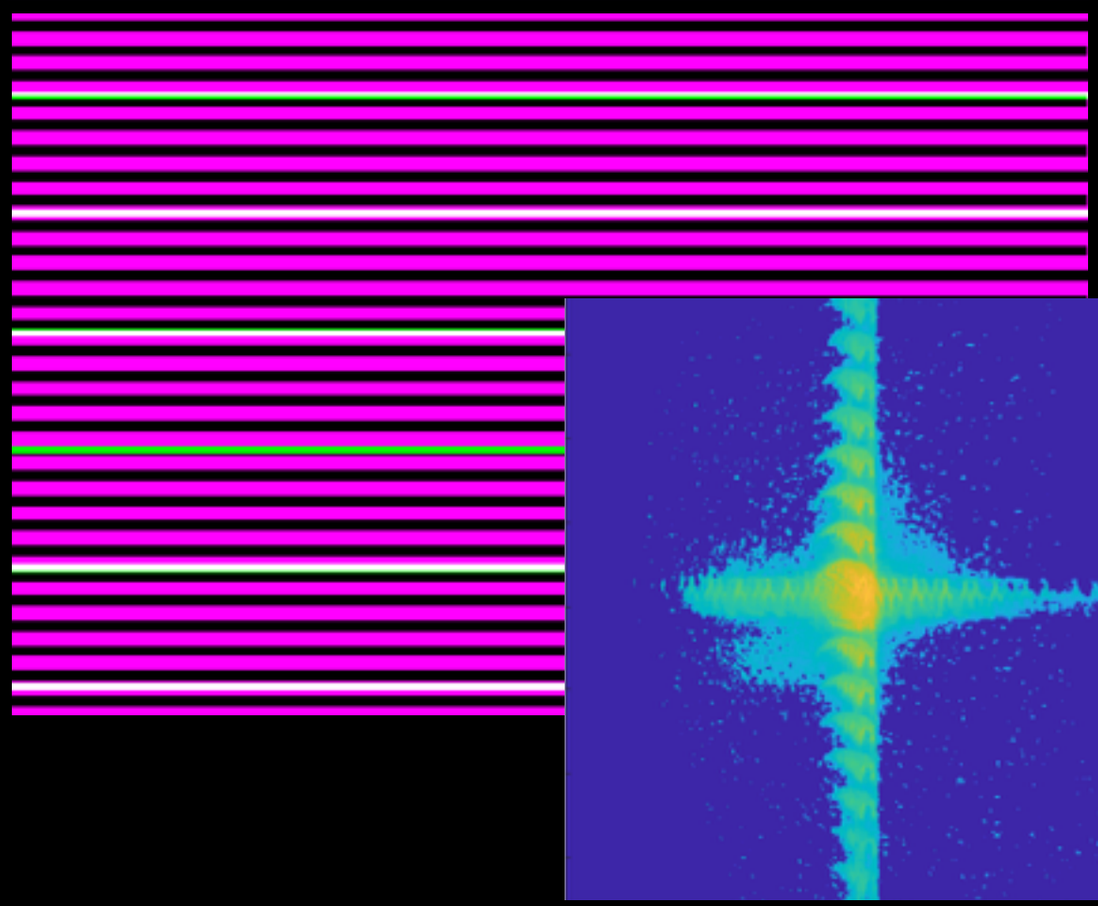
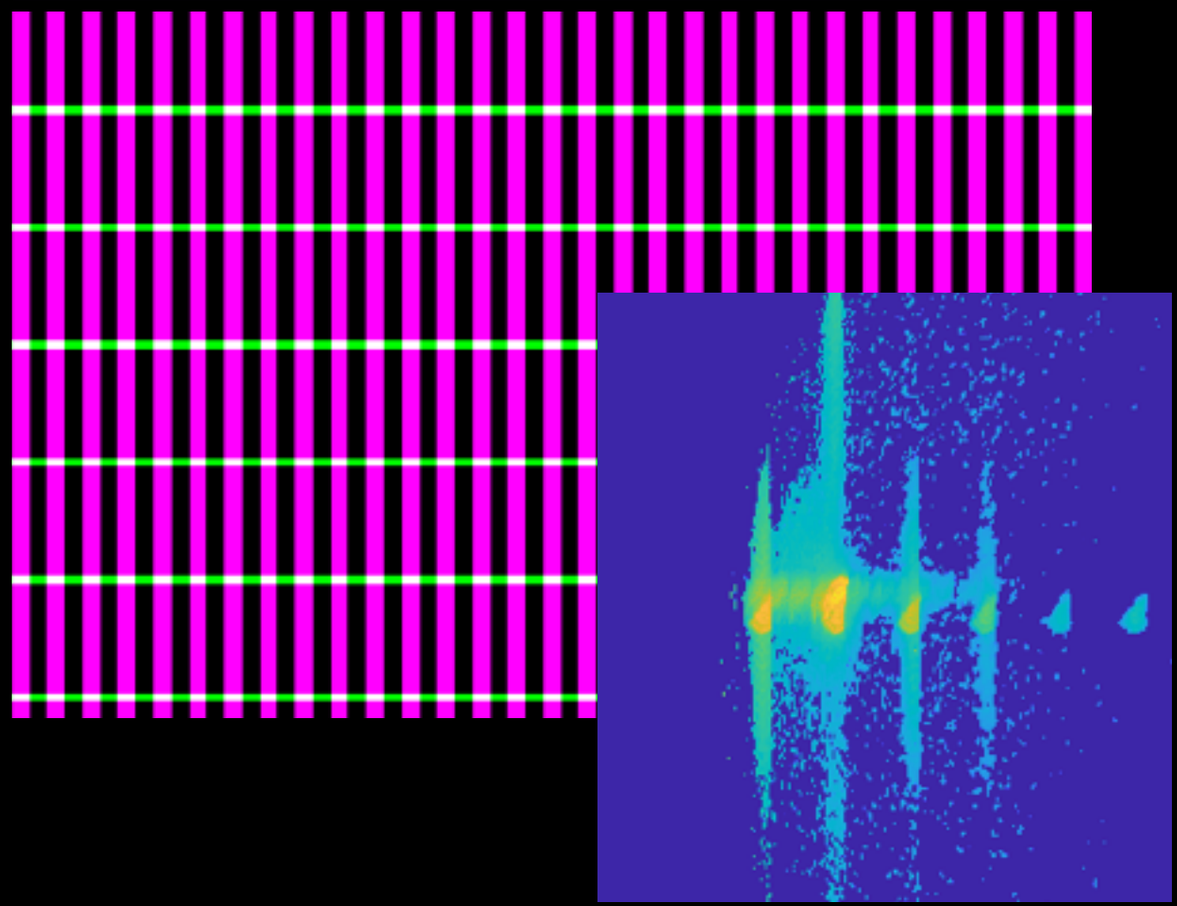


We have collected 13nm data in several regions of this sample, including 15 ptychographic datasets (12 -28°) on same field of view. Reconstructions and data analysis are in process.

Doped Regions: Magenta (400 nm pitch)
Structures: Yellow (1.9 µm pitch)



Doped Regions: Magenta (570 nm pitch)
Structures: Yellow (1.9 µm pitch)



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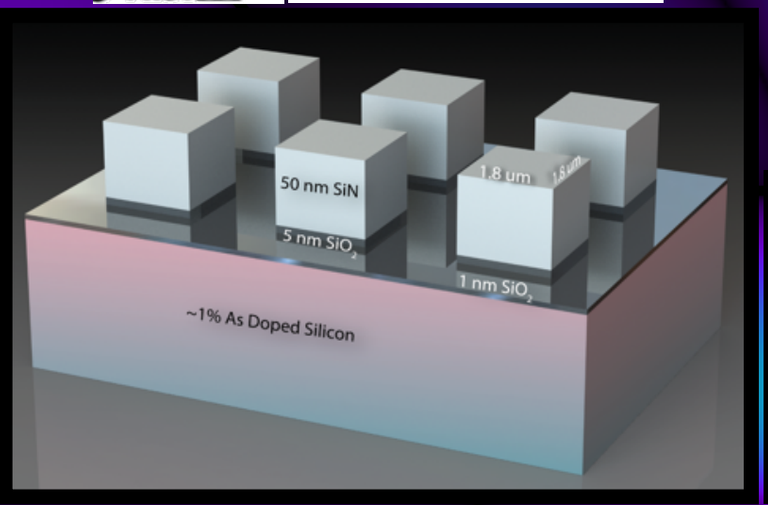

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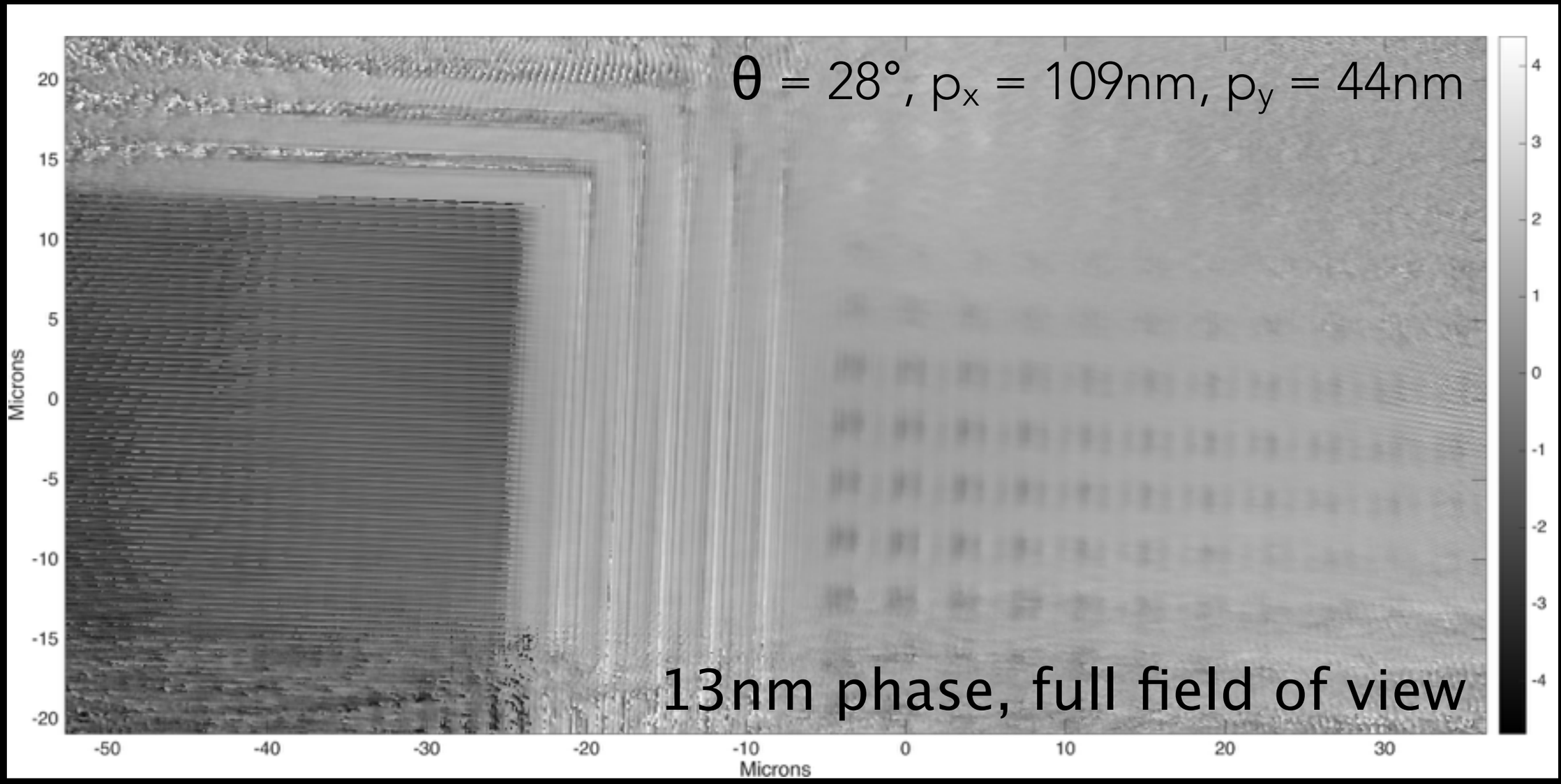

Results in preparation.

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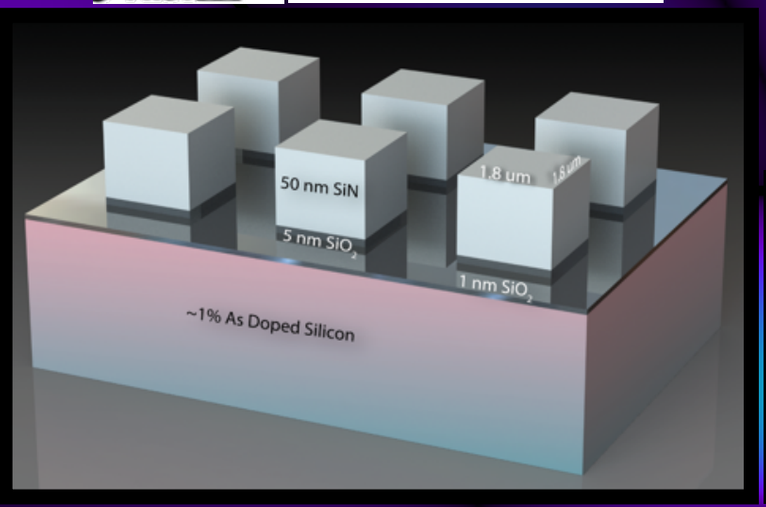

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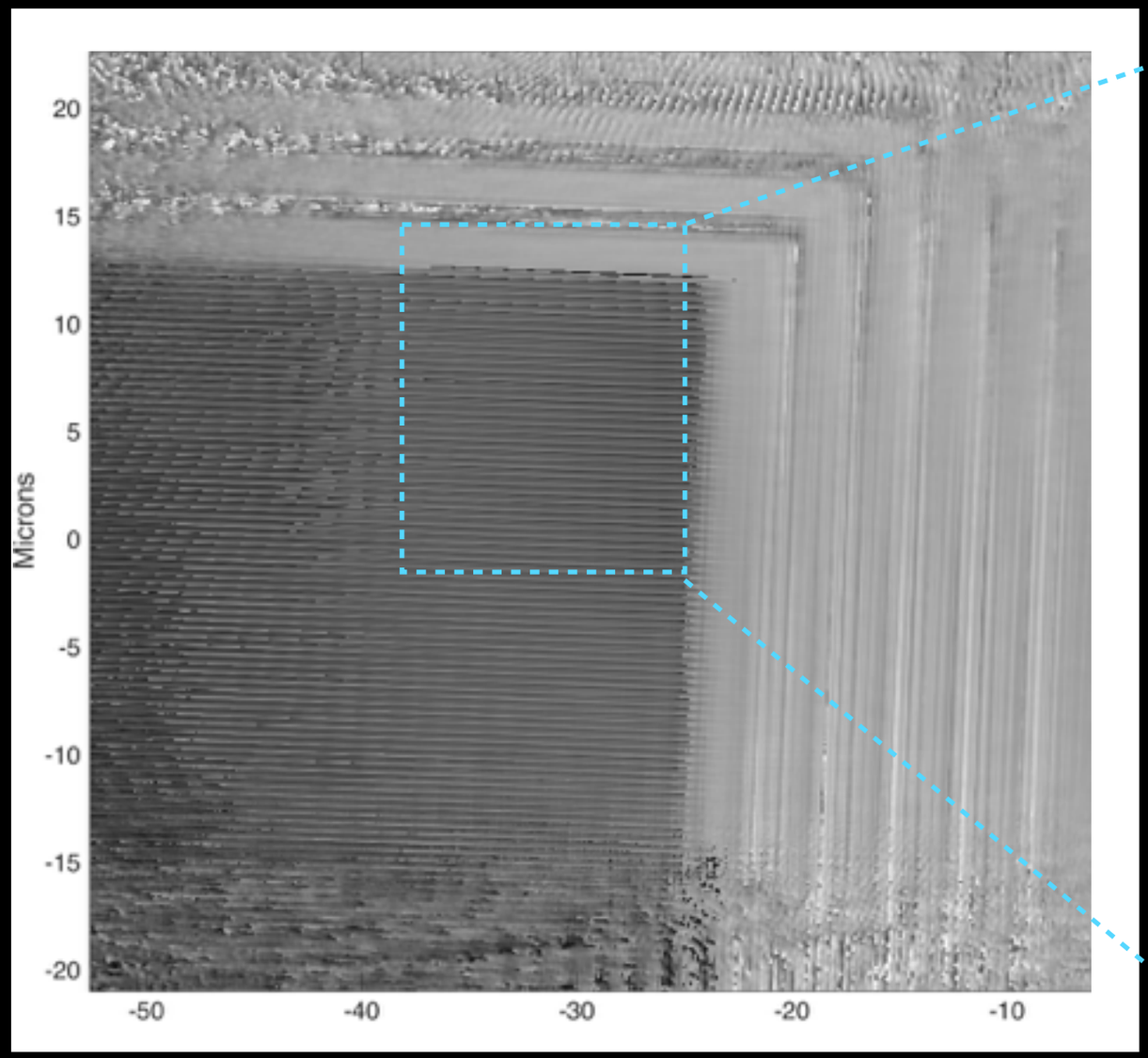
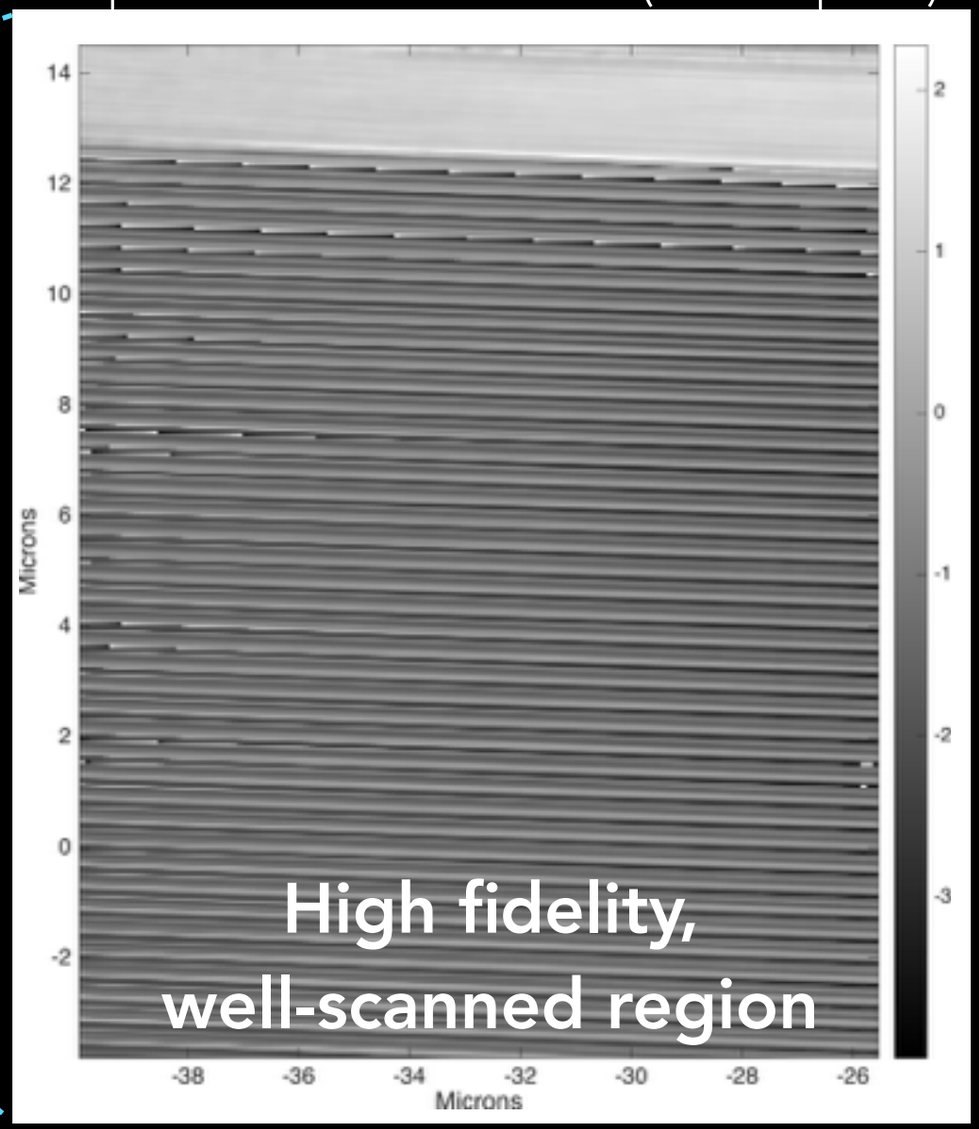
Dopant lines well resolved (400nm pitch)

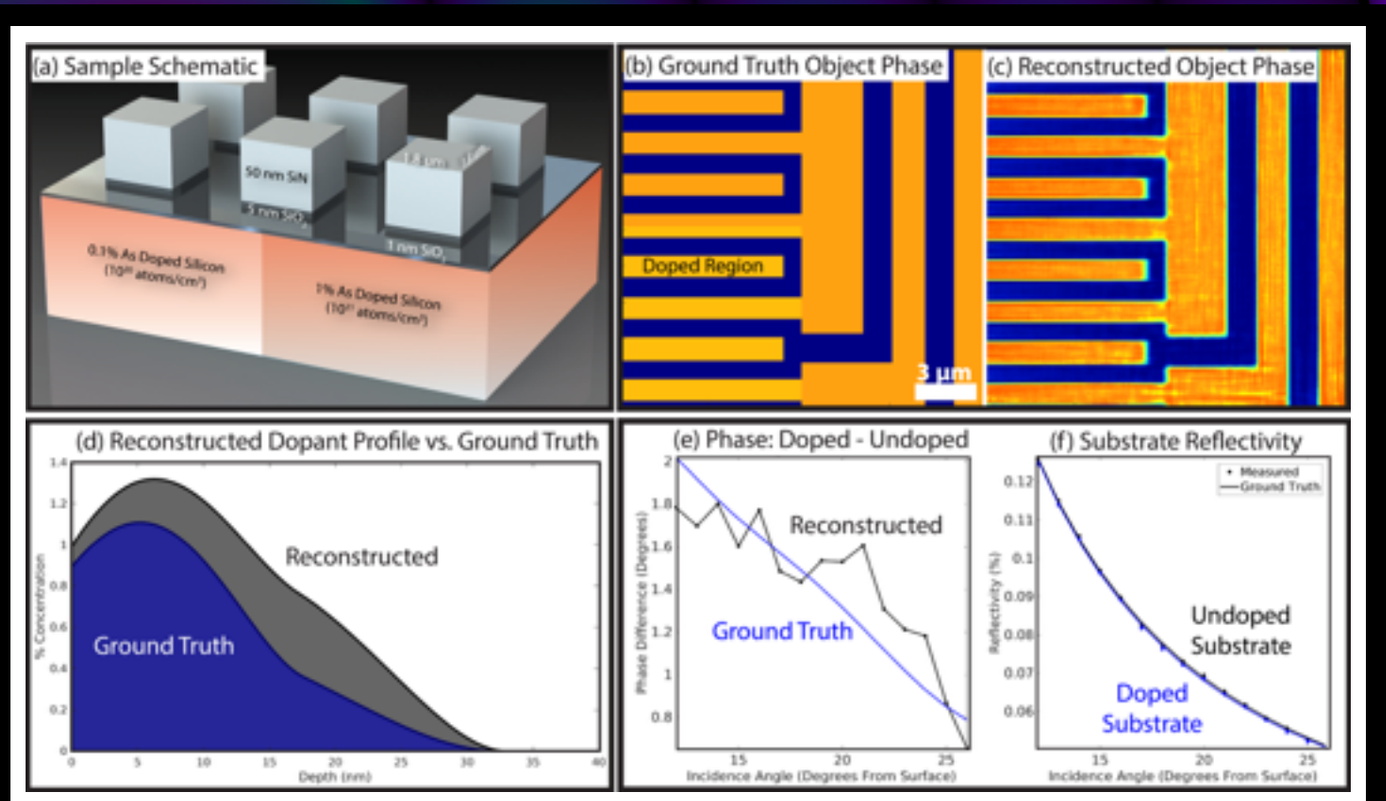




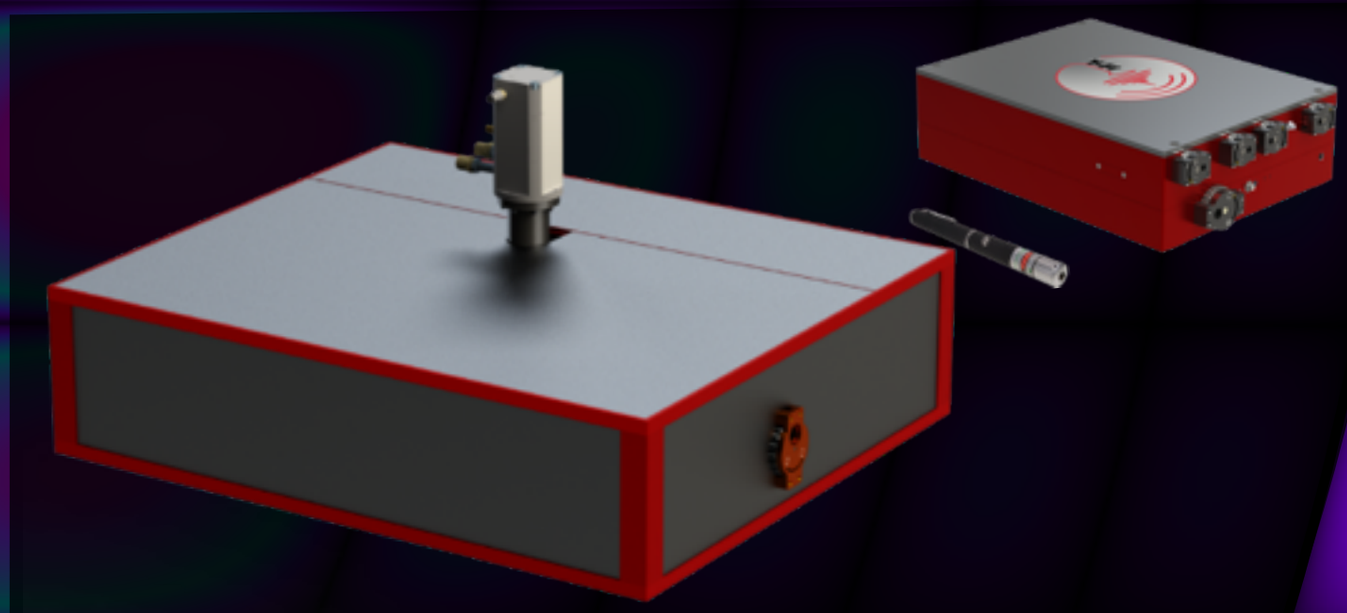
Results in preparation.

Next Steps

Carry out 3D composition reconstruction from ptychographic image set; Move to higher NA; Magnetic imaging

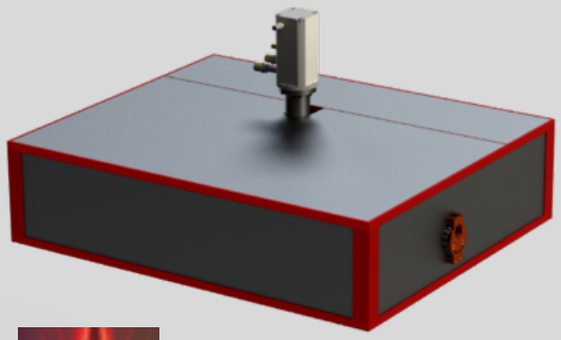


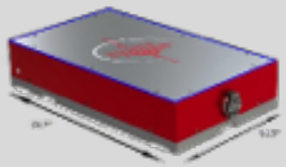
Next gen engineered laser systems and imaging/metrology instruments



Moving beyond prototypes: Next Gen Lasers for scaling EUV flux

1. RAEA, Stryde (Ti:sapphire)





EUV XUUS

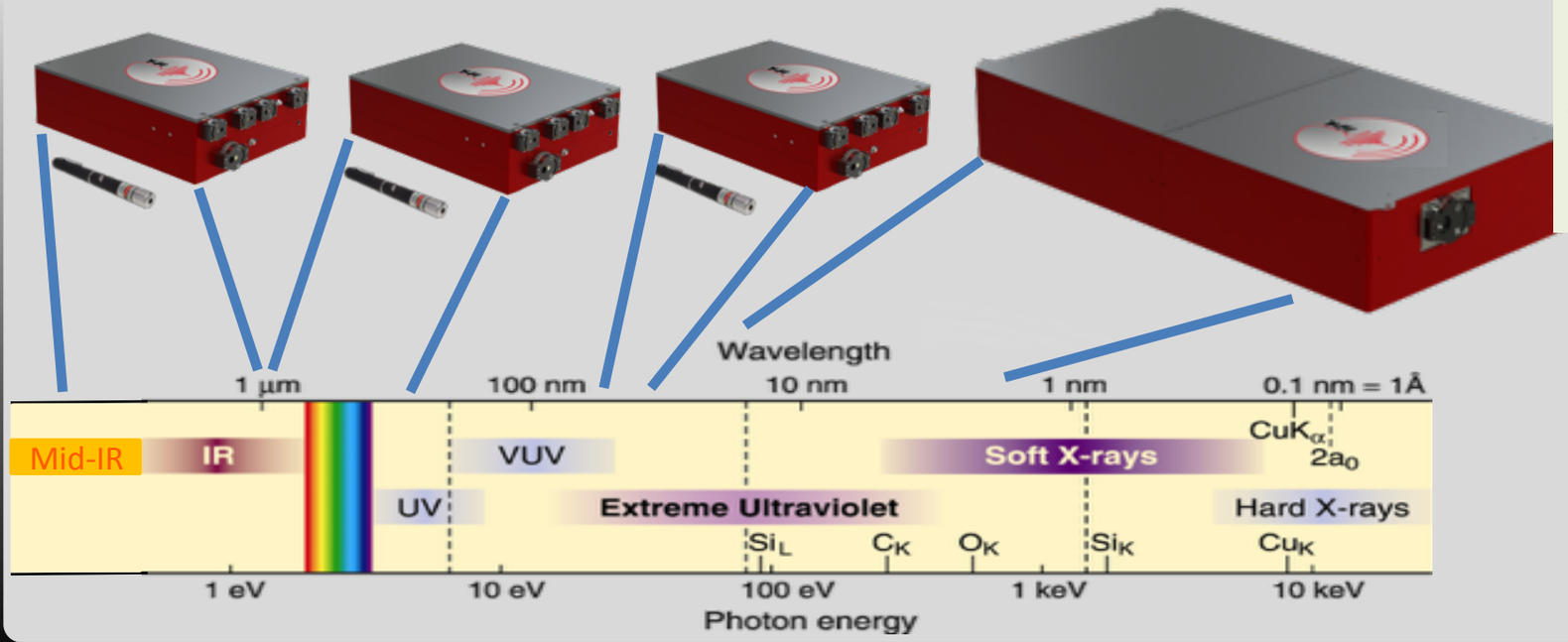
Laser Focus World Platinum Award

VUV to EUV

- New award-winning RAEA: 1-stage 28W laser
- Direct-diode pumped Ti:sapphire
- Control over linewidth, polarization, spectrum

2. Y-Fi™ fiber laser series

Y-Fi™ OPA Y-Fi™ SHG Y-Fi™ VUV Y-Fi™ Ultra/OPCPA



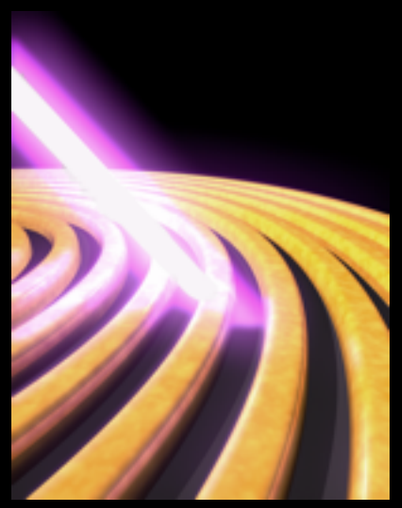
VUV to EUV to soft X-ray

- KMLabs Y-Fi fiber lasers optimized for HHG
- Control over linewidth, polarization, spectrum

Conclusions

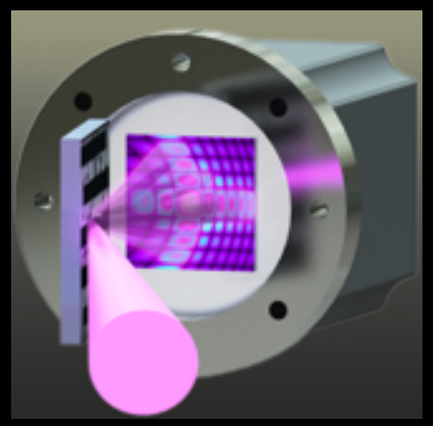
Buried layer imaging

highly sensitive to interface profiles; quantitative composition determination possible



13nm Transmission

sub-wavelength resolution imaging of nearly-periodic structures achievable using modulus enforced probe



13nm Reflection

imaging near grazing allows wide field of view & directional high resolution on general samples, so long as spatially dependent oversampling is considered

Complex Imaging Reflectometry

non-destructive 3D quantitative characterization; with sensitivity to chemical composition, layer thicknesses, dopant profiles, etc; tool supports <20nm transverse resolution

Acknowledgments

- **Current Grad Students:** Michael Tanksalvala, Galen Miley (Northwestern), Yuka Esashi, Robert Karl, Charles Bevis, Peter Johnsen, Bin Wang
- **Former Grad Students:** Dennis Gardner, Elizabeth Shanblatt
- **Scientists:** Michael Gerrity, Daniel Adams, Giulia Mancini
- **Group:**
  - Prof. Henry Kapteyn and Prof. Margaret Murnane (JILA & KM Labs)
- **Collaborators**
  - imec (Naoto Horiguchi, Philippe Leray), KM Labs (Xiaoshi Zhang, Seth Cousin), SEMATECH
- **Funding Sources:**
  - NSF STROBE Center, DARPA, Gordon and Betty Moore Foundation

Thank you!
Questions?

Ptychographic
Angle-Dependent
Reflectance
For
Analyzing
Internal
Three-Dimensional
Structure

christina.porter@colorado.edu